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[*Continued on page (III) of Cover.*

PRACTICAL ASPECTS OF EARTHING

By E. FAWSSETT, Member,* H. W. GRIMMITT, Associate Member,† G. F. SHOTTER, Member,‡ and H. G. TAYLOR, D.Sc.(Eng.), Associate Member.§

(*Paper first received* 29*th November, and in revised form* 21*st December*, 1939; *read before the* TRANSMISSION SECTION 14*th February*, 1940.)

SUMMARY

Earthing is first considered in relation to the various regulations applicable in Great Britain. These regulations relate to the generation, transmission and use of electricity, and the last item covers use in all types of consumers' premises. Particular attention is given throughout the paper to the peculiar difficulties attendant upon supply in rural areas, where protection is difficult to obtain. The factors affecting the resistance of earth electrodes are their size and shape, and the resistivity of the soil. All these items are dealt with in detail, including an analysis of the effect of rainfall on electrodes, both with and without artificial treatment. This analysis is based on the results of E.R.A. tests which have been in progress for 7 years. Only brief reference is made to the means of avoiding voltage gradients around earth electrodes which are dangerous to cattle, since this has been fully considered elsewhere. Current loading capacity is treated somewhat more fully in view of the important nature of the work and the fact that this is the first occasion on which any such results have been made public. The paper concludes with a section on the design of earth electrodes in which an attempt is made to correlate all the essential features bearing on electrodes, to show them in their true perspective in relation to the whole problem of earthing, and to relate the whole to practical requirements in which the question of cost plays a very important part.

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(1) INTRODUCTION

The practice of earthing is as old as that of electrical engineering; in fact it is older, for it dates back to the days when electricity was no more than a scientific study which scarcely interested the engineer. Earthing was then effected by touching the charged body with the finger, whereupon the charge leaked to earth. From this time the practice has passed through many phases, though customs die hard, as shown by the 1937 report of electrical accidents in factories and workshops, which states that " another instance was found where the end

* The North-Eastern Electric Supply Co., Ltd.
† Electricity Commission.
‡ Northmet Power Co.
§ Copper Development Association (formerly with the British Electrical and Allied Industries Research Association).

of the earth wire was put into a bucket of water, the bucket being specially purchased for the purpose and usually placed on a piece of wood ' to avoid leakage.' "

At the other extreme, and typifying the very latest practice, may be cited the proposal to install eight 32 ft. $\times \frac{1}{2}$ in. diameter copper rods at a Central Electricity Board substation to secure a resistance of less than 1 ohm, in soil having a resistivity, near the surface, of 15 000 ohm-cm. Before 1914 such a resistance would not have been obtained in such soil; in more recent times it might have been obtained, but at a cost at least several times greater than is required to-day; it is now a relatively simple matter.

Earthing practice is a good example of the well-known fact that until a quantity can be measured and expressed numerically knowledge is restricted and improvement is slow. For this reason great credit is due to those firms which have produced simple forms of earth testers which can be used as readily as an insulation tester. By their use engineers have realized in some measure the limitations of methods of earthing which had been used for many years, they have realized the important effect of the resistivity of the soil, and finally they have found by very few tests that some methods of earthing give a much lower resistance for a given cost than others.

American engineers profited by a comprehensive publication on earthing issued by the Bureau of Standards in 1918. The recommendations of this report, which are still quoted, were well in advance of British practice at the time, though much has been done to make up the leeway during the last few years. Driven electrodes are now being widely used, and in two important fields, viz. voltage gradients on the ground surface around electrodes and current loading capacity of electrodes, the principal progress has been made in this country. E.R.A. research has also shown how the earth resistance of overhead-line towers may be measured without disconnecting the earth wire—a problem in measurement the solution of which is actually of greater importance in other countries than in Great Britain.

All the information necessary to design electrodes economically on a resistance basis is now available and is being used to an appreciable extent. All the research work that is necessary has been done on the problem of voltage gradient, though it is not as widely known as it should be. The loading-capacity problem is still under examination; sufficient information is available to provide a lead in all soils and to give a good guide in clay and loam; when this problem has been completely solved it will be possible to design electrodes for any condition with as much precision as that of the electrical appliances which they protect.

For several years past the E.R.A. has been carrying out investigations into the fundamental problems connected with earthing, and a number of reports have been published. It is considered that the present time is an appropriate one to review the work which has been done, with particular reference to the practical problems of supply undertakings. All four authors have been closely associated with the E.R.A. researches, but in this paper H. W. Grimmitt and G. F. Shotter have undertaken the general review, whilst E. Fawssett and H. G. Taylor have compiled the account of the E.R.A. work necessary for the purpose of the review. Most of this account is now published for the first time.

(2) EARTHING

" ' Connected with earth ' means connected with the general mass of earth in such manner as will ensure at all times an immediate and safe discharge of energy."

The above is the definition of earthing contained in the Electricity Supply Regulations; but it has been found that it is not always easy to make a connection with the general mass of earth in such a manner as will ensure at all times a safe discharge of energy.

The problem becomes particularly serious in rural areas where the complete system, both h.v. and l.v., consists of overhead lines. In urban areas, where there is invariably a cable system, the cable sheaths may be used, and there is also a public water supply. There are, however, certain limitations to earthing to a water system, and attention is drawn to the increasing use of non-metallic water pipes. The Institution of Civil Engineers has published regulations for the earthing of electrical installations to metal water pipes and water mains. These regulations apply only to the earthing of the non-current-carrying metalwork of a consumer's installation to the water system, and an alternative form of earth electrode is generally installed for the neutral-point earth. These electrodes must have a low resistance and may be called upon to carry heavy currents.

At generating stations and large substations, system earths present little difficulty, since the structure and the cable system will give a low resistance, and in many cases in smaller substations earth electrodes in the form of copper strips or cast-iron plates or pipes laid immediately below the concrete foundation will afford a sufficiently low earth resistance. Practically the only situation where a system earth becomes difficult is the case of a pole-type substation in a rural area.

It is considered advisable to make a preliminary survey of earthing conditions in a village before installing the supply. This, unfortunately, is very rarely done, and the earthing is in many cases left to pure chance. Care should be exercised in regard to the actual position of the l.v. system earth. The pole-type substation is usually erected in the corner of a field near a gate, and it is here that cattle congregate. Quite a number have been killed by voltage gradient set up above the l.v. system earth plate due to a fault on the system.

The size of transformer and conductors, the current rating of the fuse, or the operating current of the protective gear, and the earth resistance of the system and consumer's metalwork, must all be considered and are all inter-related. In many instances the size of fuse to be installed is determined by the size of transformer, without any regard to the conductor size or the value of the earth resistance.

Not only is it essential to measure all earth electrode resistances at the time of installation, but also periodic tests should be carried out.

The village earthing problem is being relieved by the fact that during the last five years there has been considerable development of piped water supplies in rural

areas, though there are still many villages and hamlets in the United Kingdom without such a supply.

(a) High-Voltage System Earths

Regulation 8 of the Electricity Supply Regulations, 1937, sets down conditions under which earthing shall be undertaken. It states that there must be only one neutral-point earth on each high-voltage system. Should more earths be required, then it is necessary to secure the consent of the Electricity Commissioners, who serve additional regulations on the undertaker when such an application is approved. These additional conditions have been framed by the Electricity Commissioners in conjunction with the Postmaster-General, and their main object is to prevent telephone interference.

It must be strongly emphasized that the value of the earth has an important bearing on the operation of h.v. fuses and the protective gear installed. Earth-leakage protection installed at the main points of an overhead ring main will ensure the safe operation of the switches by a high-resistance fault. A conductor falling to the ground will be, in the majority of cases, a high-resistance fault. If when the conductor falls, the line is not cleared, such a fault may result in a serious accident. The Postmaster-General sometimes requires that the high-voltage system earth connection shall have a resistor inserted to limit the short-circuit current.

Resistance earthing and so-called "solid earthing" are general in this country. Reactance earthing of the type practised in America is practically unknown, but tuned reactances (i.e. Petersen coils) are now being installed to an appreciable extent.* These coils are short-circuited occasionally, and consequently the earth resistance must be such as is required on an ordinary earthed system. Furthermore, the current-loading capacity of the electrode must be similar to the overload characteristic of the coil.

(b) Low-Voltage System Earths

Regulation 4 of the Electricity Supply Regulations, 1937, sets out the requirements in the United Kingdom for low-voltage system earths. It is necessary to earth each system, fed by a substation, at one point, and the neutral conductor should be insulated throughout its length.

If it is desired to interconnect two or more systems, as is usual in urban areas, each substation may be earthed, and the neutral will then be common to the system. Before this is done, notice must be served by the undertaking on the Postmaster-General.

If an undertaking requires to earth the neutral from one substation at more than one point, the system must be approved by the Electricity Commissioners under Regulation 4 (ix).

In rural areas where the villages are far apart, and where each village is, as a rule, fed from one substation, the question of low-voltage neutral interconnection does not occur, and it is here that the difficulty of earthing arises. On urban low-voltage systems it is generally easy to secure low resistances to earth, but in rural areas, where water mains are frequently not available for earthing, there are serious difficulties. If it is proposed to work according to the Regulations with just one earth, it is quite obvious that the substation earth resistance must be very low—that is, something less than 5 ohms—and this is frequently very difficult to secure.

* H. W. Taylor and P. F. Stritzl: *Journal I.E.E.*, 1938, **82**, p. 387.

(c) Earthing of High-Voltage Overhead-Line Supports

In practically all instances in this country where overhead lines have latticed steel towers for supports, these lines carry a continuous earth wire, the function of this wire being to ensure that all extraneous metalwork is at earth potential, and to act as a release for fault current and as a protection against lightning. It has been generally accepted that to make a line secure against lightning it is essential that the continuous earth wire should be earthed at each tower and that this resistance should be less than about 10 ohms.* The foundations alone of such towers sometimes have a sufficiently low resistance for other protective purposes.

To obtain such low resistances is a difficult problem. On some lines erected in America one or more copper conductors of fairly substantial size have been buried the entire length of the line. The continuous aerial earth wire is bonded to each tower, and each tower is in turn bonded to the buried earth wire. This is of course rather a special precaution.

Considering ordinary single-circuit lines supported on wooden poles with a continuous earth wire earthed at four points per mile, the earth wire is only a partial protection against lightning. Its efficiency depends entirely on the resistance of the earth electrodes, and in many cases it is impossible economically to install them so that their resistance is of a really effective value. It is perhaps for this reason that h.v. lines supported on wooden poles without a continuous earth wire and without their metalwork being earthed at each pole are reported to be more free from lightning trouble than those with a continuous earth wire.

Where a continuous earth wire is used, a certain measure of safety is provided, since the majority of these lines are protected by fuses and the resistance of the earth-return circuit when a conductor comes in contact with the cross-arm will practically always be sufficiently low to cause the fuses to blow. This state of affairs might not occur, however, if the individual metalwork were earthed at each pole.

The electrode earthing the continuous earth wire and the metalwork of a transformer should be kept well away from the l.v. system earth.

(d) Consumers' Apparatus

(i) General.

The earth resistance at consumers' premises should be sufficiently low to blow the largest fuses, but often this is economically impossible. This state of affairs has led undertakings to consider protective multiple earthing, neutralizing, or earth-leakage circuit-breakers. The ordinary 18-in. square earth plate or the 3-ft. earth rod is of very little use in the majority of soils found in rural England. There are a number of methods for

* *Electrical Engineering*, 1939, **58**, p. 304 (Transactions Section).

obviating this difficulty. Some undertakings have run a fifth wire on the overhead lines, and this wire has been earthed along its route to some fortuitously low earth; this is generally found somewhere in a village where there is either a small isolated water system or a pond. This expedient is not considered good practice by some engineers, since in the event of the breaking of this wire the protective metalwork on electrical apparatus at the consumers' premises becomes unearthed. Furthermore, contact between a live wire and the earth wire represents a serious potential danger.

With ordinary earthing in a rural area, it is obvious that care must be taken in selecting the correct size of fuse both at the consumer's premises and at the substation, and this size of fuse is more dependent on the earth resistance than on the size of the transformer. It means in fact that if it is impossible to get below a certain figure for the earth resistance, then it is not possible to install a transformer above a certain size. It is known that many undertakings ignore these matters and that there must be in use many systems in which, should an earth fault occur even close to the substation, the fuses would not blow.

Protective multiple earthing is an alternative form of protection which is not common in this country. It is fully described in E.R.A. Report Ref. F/T102,* and the Commissioners have issued Regulations, based on this Report, for those who desire to use the system. Certain of the recommendations in the report referred to were made with a view to increasing the safety of a multiple-earthed system should the neutral break. It has since been shown that this possibility cannot be ignored, and dangerous conditions will arise if the neutral breaks unless the neutral resistance to earth is extremely low. If, on the other hand, it is possible economically to get the neutral resistance to earth to such a low figure that protective multiple earthing will be absolutely safe in all conceivable circumstances, then it will be unnecessary to use this system because ordinary earthing should prove quite satisfactory.

Ordinary earthing—that is, one system earth at the substation and the consumer's earth utilizing the public water mains or the cable sheaths—has proved quite satisfactory in urban areas and has been the general practice in this country. The main difficulty with ordinary earthing occurs when the system is overhead and is situated in a district without a piped water supply. The use of strip electrodes has been the means of reducing substation earth resistances to a reasonable figure, and deeply driven rod electrodes have also proved useful. However small the substation electrode resistance, it is useless unless the consumer's earth resistance is also of a low value.

Earthing in consumers' premises should be carried out in accordance with the Electricity Commissioners' Regulations, the Institution of Electrical Engineers' Regulations, or the Home Office Factory Regulations, appropriate extracts from which are given in Appendix I. Whatever regulations are used, an important feature which is generally applicable, and to which attention should be drawn, is the necessity for ensuring that the connection to the electrode is so large and durable that it will not be fractured mechanically or by corrosion, and that the connection to the electrode is likely to remain permanently satisfactory.

* *Journal I.E.E.*, 1937, **81**, p. 761.

(ii) Protective multiple earthing.

This is a mixture of system and apparatus earthing; the non-current-carrying metalwork of the consumer's apparatus is connected to the neutral, and the neutral is earthed at various places along its route and at each consumer's installation.

This system (or modified forms of it) is very popular on the Continent, and is used fairly extensively in the Dominions and America. Most countries have special regulations and conditions, and the Electricity Commissioners in framing their regulations have followed the recommendations which are embodied in the E.R.A. Report Ref. F/T102. These regulations go a little further than the conditions laid down in other countries.

There has been little experience of this system in this country, and protective multiple earthing in a rural area where it is difficult to obtain low earth resistance must not be confused with a system in an urban area which adopts concentric wiring in the consumer's premises and the bare outside casing is used as the neutral. This system is of course perfectly safe, providing that the concentric covering remains a continuous low-resistance conductor, and no danger or difficulty has been experienced with it, chiefly on account of the fact that in an urban area it is quite easy to get a very low earth resistance.

The conditions are different in country districts, and the regulations made by the Commissioners are for protective multiple earthing in such areas only. The main problem is to reduce the overall resistance to earth of the neutral to as low a figure as possible. The regulations require not less than four electrodes per mile and that the earth resistance of each shall not exceed 10 ohms;* this may be difficult to obtain with an individual earth electrode. Other countries suggest that the total resistance to earth of the neutral shall not exceed 5 ohms. In some recent tests where it was difficult to get below a figure of 80 ohms with the ordinary (6 ft.) rod electrode (this being a particularly difficult high-resistance area) the calculated overall resistance of the neutral was approximately 4·7 ohms, so that it appears that in practice it should not be difficult to obtain an overall resistance of the neutral to a figure of 5 ohms or below.

As in all systems of protection, the size of conductor and the size of fuse are important, and the regulations do not permit a conductor section of less than 0·05 sq. in. for the neutral.

In this country, where low-voltage mains seldom run for more than ¾ mile from a substation, little difficulty is experienced. It is only on long small-conductor lines that the neutral resistance plays an important part.

The regulations also require that the neutral shall be earthed at the consumer's premises, and that the elec-

* An alternative which has since been proposed is that an earth having a resistance of not more than 10 ohms shall be connected to the neutral at the end of each distributor, and such additional earth electrodes shall be provided that the total resistance to earth of the neutral of any group of distributors fed by one line direct from the transformer shall not exceed 2 ohms, and further that these additional earths shall be approximately equally distributed.

trode shall be in the form of a 6-ft. earth rod; this is to give a measure of safety in the event of the service neutral breaking. Other countries do not always require it. From a questionnaire circulated it seems that very few neutral services break alone in this country, but, on the other hand, if these electrodes are not included then it is necessary to use twin or concentric services so that there is no possibility of the neutral breaking without the phase wire.

One of the dangers with protective multiple earthing is the fact that all non-current-carrying metalwork in premises is connected to a common neutral, and a heavy uncleared fault in one of the premises may raise the neutral voltage to earth and therefore the non-current-carrying metalwork in all the other premises may be dangerous. Certain tests have been carried out on protective multiple earthing systems, and they indicate that under severe unbalanced loads the rise in potential of the neutral is not serious, and that it can be said definitely that a protective multiple earthing system under normal working conditions is much safer than a system earthed in the usual way.

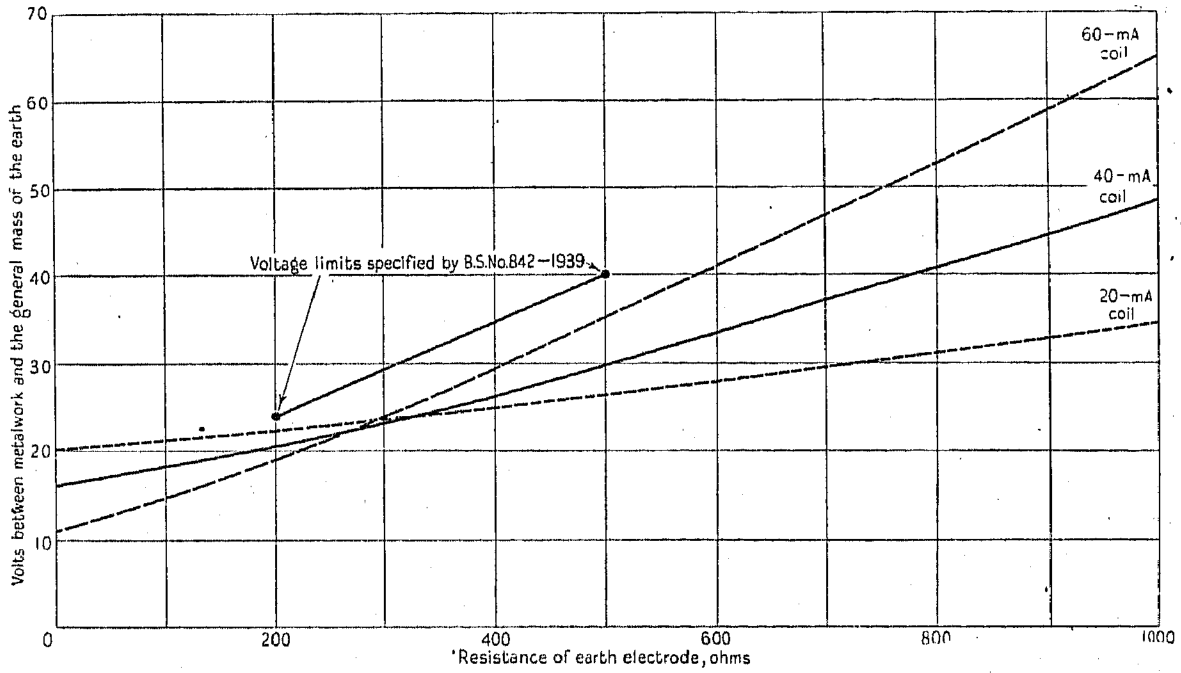

Fig. 1.—Relationship between shock voltage and earth resistance for various trip-coil characteristics. (Data from typical earth-leakage circuit-breakers.)

(iii) Neutralizing.

The chief disadvantage of protective multiple earthing is the danger arising from a broken neutral conductor, and this, although rare, cannot be entirely ignored. To minimize the risk, the earth resistance of the neutral is made as low as possible, and earths are provided at all consumers' premises. Where the soil resistivity is high (as would generally be the case—otherwise ordinary earthing would be satisfactory) this represents a serious expense, and it is considered that the money might more advantageously be expended in ensuring that in the event of a neutral only breaking it would make contact with a live wire and so blow the fuse and disconnect the supply from the faulty section.

In such a system there would be no need for more than a single earth, which could be situated at the substation, and investigation is taking place into the design of guards, reinforcements, etc., with a view to ensuring the advantages of a protective multiple earthing system without the disadvantages arising from a broken neutral distributor or service wire. Such a system, where all the metalwork was connected to the neutral and the neutral earthed only at one point, would be described as "neutralizing." Whilst this method of protection has distinct advantages over protective multiple earthing, it should not be overlooked that there is still the possibility of appreciable voltage-rise on the frameworks of apparatus during the period immediately before the fuse blows.

(iv) Earth-leakage circuit-breakers.

The use of earth-leakage circuit-breakers has been fully discussed in the past in the technical Press, and in particular is dealt with in two recent E.R.A. reports.* It is therefore not proposed to go into the subject again. It is desirable, however, to emphasize that although earth-leakage circuit-breakers will function with a much higher resistance than is possible with ordinary earthing, it is, nevertheless, necessary to pay some attention to the installation of the electrode. The effect of earth resistance on the shock voltage to be obtained from earthed metalwork is shown in Fig. 1 for three representative earth-leakage circuit-breakers complying with B.S. 842—1939. This specification requires that earth-leakage circuit-breakers shall operate at not more than 24 volts when the earth resistance is 200 ohms and 40 volts when it is 500 ohms. Resistances in excess of this may often occur with small electrodes in some soils, and care should be taken, by means of earth-resistance measurements, to avoid this.

As earth-leakage circuit-breakers have been mostly used in connection with cookers in this country the principal practical difficulties which have been experienced are a tendency to trip due to (*a*) low-insulation-resistance boiling-plates, (*b*) boiling-over of liquids, (*c*) condensation on the switch terminal block due to proximity of the switch to the cooker.

* Refs. F/T102 and F/T122.

(3) HISTORICAL SURVEY OF TYPES OF ELECTRODES AND THEIR USES

Earth electrodes may be divided into two classes—those which are used as earth electrodes only, and those which are primarily used for some other purpose. The first class comprises plates, strips, conductors, pipes, rods and all kinds of specially designed electrodes. The second class comprises water pipes, frameworks of buildings, well linings, and cable sheaths and armouring. Of this class, water-pipe earths are the most common, and are very frequently used in earthing house and building installations. Generally speaking, such earths, if extensive and of all-metal piping, are of low resistance. On a completely underground network, cable sheaths have the very great advantage that they provide a metallic return path to the substation entirely through the property of the supply authority.

The commonest type of earth electrode in this country for use at power stations and substations is still probably the cast-iron plate, though buried cast-iron pipes are frequently used. At power stations the circulating-water pipes may be employed as electrodes. Ten years ago the use of driven rods or tubes, and buried strips or conductors, was practically unknown in this country, though such electrodes were the commonest type in America, where the buried pipe or plate is very rarely used. The position has appreciably changed to-day, and large numbers of small-diameter electrodes are being driven. The usual size of electrode is $\frac{3}{4}$ in. or 1 in. diameter by 6 ft. long, though recent developments in driving technique employing an electric hammer have made it possible to drive $\frac{1}{2}$-in. diameter rods to considerably greater depths and in general to obtain a given value of resistance at less outlay in time and material. Rod and tube electrodes are particularly suitable for earthing overhead lines, rural substations, and consumers' installations, and are widely used for all these purposes. Buried strips and conductors are also being used, particularly for rural-substation earthing, in locations where there is a superficial layer of low-resistivity soil over a high-resistivity material such as chalk or the igneous rocks.

Another form of electrode which has been developed experimentally is the coke trench or bed. This is a logical extension of the old process of coke-treated electrodes, the real effect of which is to increase the size of the electrode relative to that of the coke bed. In the new method the size of the metallic electrode relative to the coke has been very considerably reduced, so that one can genuinely regard the combination as a coke electrode with a small metallic connection to it. A particular field of utility has not yet been found for this type, but it would appear to be suitable for use where the soil resistivity is not too high and where extensive trenching or excavation for pipes or foundations must be carried out, or where a layer of coke breeze could replace a bed of clinker for drainage purposes.

Earth plates are generally made from cast iron or copper. They are buried at an average depth of from 4 to 8 ft., although greater depths are sometimes used in order to get below the subsoil water-level. The plates are laid either horizontally or vertically, but the latter is widely considered, in the U.S.A., on the Continent, and in this country, to be the better practice on account of the smaller excavation required and the difficulty of obtaining a sufficiently good contact with the soil underneath a horizontal plate. The copper conductor is soldered, riveted, or welded to the plate, or it may be expanded in by means of a type of tramway bond using a tapered steel bullet to expand the copper connector. Soldering is generally deprecated, as it may cause corrosion. Corrosion also occurs when the copper lead is welded or riveted to an iron or steel plate, but not apparently to such a marked extent. Earth plates vary considerably in size. Records are available of one 18-in. square plate being used for a substation and of ten 6 ft. × 3 ft. plates being used for a power station.

The chief advantage of buried pipes over plates is that the pipe may project above the surface, and any deterioration of the connections may therefore be detected by inspection. Buried earth pipes are a costly proposition, and very elaborate arrangements are sometimes used. A case in point exists where ten 9-in. diameter pipes, 18 ft. long, are used in two groups of five each. The most usual size appears to be from 6 in. to 9 in. diameter and 6 ft. to 12 ft. long. Both pipe and plate earths are sometimes provided with arrangements for keeping the surrounding soil moist. This is effected either by directing rain water from waterspouts to the electrode or by providing special watering arrangements.

There is no evidence to indicate that any appreciable change in preferred type of earth electrode has taken place on the Continent in recent years. Opinion seems to be generally divided between strips, plates and pipes. In America the situation has been fairly static, though the necessity for securing low tower-footing resistances to assist in lightning protection of overhead lines has resulted in electrodes being more deeply driven than previously, and mechanical hammers are being used to facilitate driving. The same cause has induced a development of the buried strip or conductor electrode into a counterpoise which may either take the form of several electrodes buried radially around the base of a tower or may consist of one or two wires buried 2–3 ft. below the ground-level and interconnecting the towers over the whole length of a line or over a particular portion which is especially exposed to lightning. In Great Britain such troubles are less serious than elsewhere, and it has not so far been necessary to use counterpoises. Earthing practice is probably changing here more rapidly than elsewhere in the direction of substituting driven for buried electrodes, and further changes are likely to take place in the direction of increasing the life and reducing the cost of electrodes. A more scientific approach towards the question of voltage gradient on the ground surface, and relating to the loading capacity of electrodes, is also being adopted.

(4) FACTORS AFFECTING THE RESISTANCE OF ELECTRODES

(a) Effect of Size and Shape

(i) Rods and tubes.

The resistance of a single rod or tube electrode is given by the formula

$$R = \frac{\rho}{83l} \cdot \log_{10}\frac{48l}{d}$$

where ρ = soil resistivity, in ohm-cm.;
l = length of electrode, in feet;
and d = diameter of electrode, in inches.

A curve based on this formula is shown in Fig. 2, where the earth resistance of a ½-in. diameter electrode is plotted against the length, for soil having a resistivity of 1 000 ohm-cm. Where the soil resistivity has some other value, say ρ', the resistance may be determined by multiplying the value given by the curve by $\rho'/1\,000$. If the diameter of the electrode is halved or doubled, the resistance is increased or decreased by approximately 12½ per cent for a 6-ft. rod, and it will therefore be clear that an increase of length is much more important than an increase of diameter. An increase of diameter of a rod electrode from ½ in. to 4 in. (i.e. an eight times

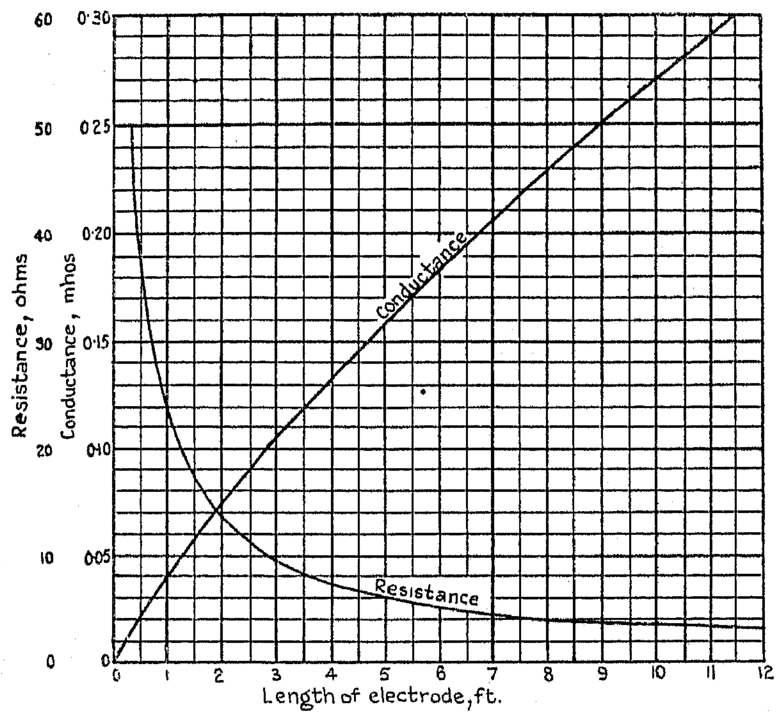

Fig. 2.—Earth resistance and conductance of a ½-in. dia. electrode in soil having a resistivity of 1 000 ohm-cm.

increase) reduces the resistance by only 48 per cent, 33 per cent, and 29 per cent for rods 2 ft., 5 ft., and 10 ft. long respectively. For this reason, to obtain the lowest resistance for a given cost, the tube or rod should have as small a diameter and as great a length as possible, bearing in mind that it has to be driven into the soil. The shape of the resistance/length curve often leads to the impression that there is little advantage in increasing the depth beyond a few feet, but this is generally an illusion, depending on the scale to which the results are plotted. A more useful curve is that of conductance against length, since the conductance is proportional to the current which flows under constant voltage, and it is the current which determines whether the circuit will be cleared by the fault. The resistance curve flattens out, but the conductance curve is practically a straight line and indicates that the longer the electrode the better.

What may be called the efficiency of an electrode is the conductance per unit length. In a soil of uniform resistivity this falls steadily as the length increases, but since the resistivity is rarely uniform this does not apply in practice. Frequently the efficiency will increase with depth, owing to reduction of resistivity, and in such cases it is probably more advantageous to increase the depth rather than to drive another electrode and connect it in parallel.* Where the resistivity increases with depth there is clearly no advantage in increasing the length; it is preferable to connect a number in parallel or to use a conductor or strip buried in a trench.

From the simple formula given above (or by using the curve), and from an approximate knowledge of the resistivity of the soil, the limitations of a single electrode, or even a practicable group of electrodes, in disconnecting a fault by blowing a fuse on l.v. networks in ground of high or even medium resistivity at once become apparent.

The advantages of small-diameter electrodes, say ½-in. dia., as compared with those of ¾-in. or 1-in. dia., are the greater ease of driving and the possibility of reaching a low-resistivity substratum by driving long lengths. Tests have been made to check both these claims. By means of a simple pile-driving arrangement, the energy required to drive various electrodes was measured, with the results shown in Table 1.

Table 1

Electrode	Foot-pounds required in clay to drive—			
	4 ft.	5 ft.	6 ft.	7 ft. 6 in.
½-in copper tube	2 000	3 200	5 200	9 800
½-in. copper-clad steel rod ..	2 800	4 600	6 800	11 000
¾-in. copper-clad steel rod ..	5 000	8 500	12 500	20 000
$1\frac{5}{16}$-in. o.d., m.s. tube	9 300	15 800	—	—

The mild-steel tube had a bore of 1 in.; this is a common size of earth electrode, but it will be noted that a ½-in. diameter rod can be driven to the same depth with the expenditure of about one-quarter of the energy. To avoid bending or deformation of the top end of small-diameter electrodes, they should be driven with a large number of relatively light blows rather than with a small number of heavy blows. If the blows are sufficiently light, the stresses in the metal of the electrode will not exceed the elastic limit, and no deformation or bending will occur. For this reason, in America it is common practice to use a 4-lb. hammer. The same result may be obtained by using an electric or pneumatic hammer where the blows are relatively light and the number per minute very large. Pneumatic hammers have been used for this purpose in the U.S.A., but in many cases possibly an electric hammer is a more convenient tool for an electricity undertaking to employ.

With a "D"-type "Kango" electric hammer it has

* There are several factors to be considered here, viz. the increased mechanical resistance to driving as depth increases, the cost of couplings, and, in the case of a number of rods, the additional cost of interconnecting leads.

been found possible to drive a 6 ft. × $\frac{3}{8}$ in. dia. hard-drawn copper rod 5 ft. 6 in. into limestone in 42 seconds, and driving rates of over 10 ft. per minute have been obtained with $\frac{1}{2}$-in. dia. rods. These are the highest driving rates so far obtained; other soils, particularly clay, have given appreciably lower rates. The feature of greatest importance with all driven rod electrodes is their cheapness for a given resistance and the fact that they may be driven through a layer of high-resistivity soil into one of low resistivity underlying it. Small-diameter coupled rods are particularly suitable for this purpose, and were used in deep driving tests made at Colchester, at Cheshunt and in Northumberland.

At each of these sites $\frac{1}{2}$-in. dia. hard-drawn copper rods were used in sections of 6 ft. or 8 ft., which were coupled together so as to form a single uniform-diameter electrode. They were driven by means of an electric hammer. At Colchester it was known from previously sunk boreholes that the first 20 to 30 ft. consisted of ballast, sand and gravel, below which occurred London clay. Two electrodes were installed, and the results shown in Table 2 were obtained.

Table 2

Depth of driving, feet	3	6	9	12	15	18	21	24	27	30	33	36
Resistance of one electrode, ohms	110	36	26	26	26	25	23	23	9·5	4·9	3·0	2·0
Resistance of other electrode, ohms	> 1 000	88	43	41	40	42	39	36	33	12	4·0	2·5

The marked reduction of resistance which occurred after striking the clay is clearly shown. It is also noticeable that there is no useful reduction of resistance between about 9 ft. and 24–27 ft. in either case.

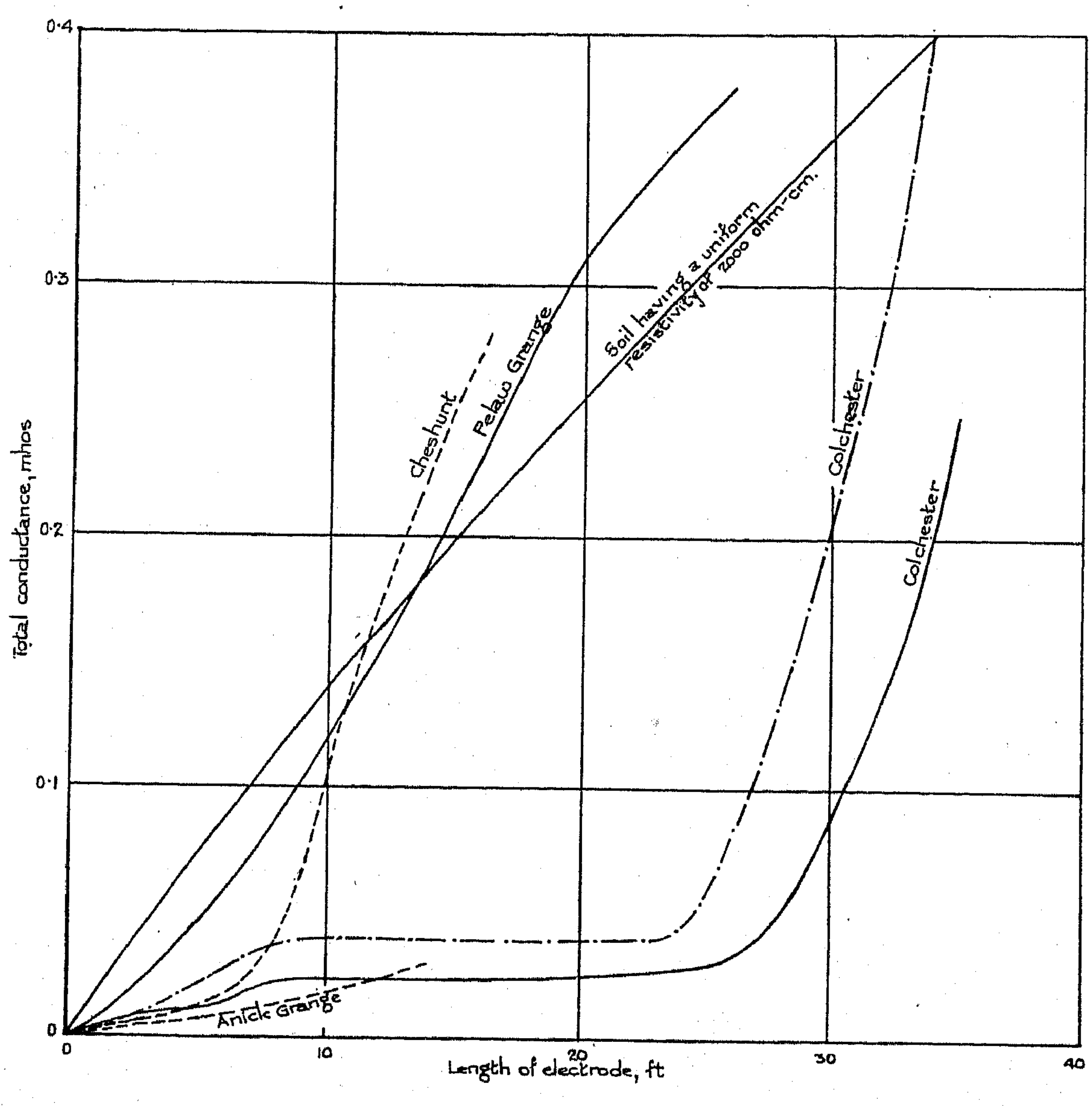

Fig. 3.—Conductance of $\frac{1}{2}$-in. dia. copper rod electrodes.

Table 3 shows the results obtained in the Northumberland area. At only three sites was it found that the resistivity diminished with depth, and in only two of them (the last two in the Table) was the reduction appreciable. At Anick Grange the average resistivity to a depth of 3 ft. was 21 000 ohm-cm., whilst the

Table 3

DEEP-DRIVING TESTS IN NORTHUMBERLAND AND DURHAM

Place	Soil: Type	Resistivity, ohm-cm.: At 3 ft.	Resistivity, ohm-cm.: At 12 ft.	Electrode resistance, ohms: Driven vertically: 3 ft.	6 ft.	9 ft.	12 ft.	Time for 12 ft. (min.)	Driven at 30° to horizontal: 3 ft.	6 ft.	9 ft.	12 ft.	Time for 12 ft. (min.)	Remarks
Barrasford ..	Peaty loam over whinstone	20 000	—	200	110	—	—	—	252	144	95	63	3	
Frosterley ..	Loam over limestone	7 500	10 200	74	47	36	32	4	80	54	37	30	4½	
Riding Lea ..	Loam over boulder clay	3 900	—	39	29	—	—	—	85	30	20	16	10	
Fourstones Quarry	Peaty loam over limestone	3 700	—	37	25	20	—	—	46	24·5	19	15·6	7	Another rod 10 yd. away took 15 min. to drive, for same resistance
Jesmond ..	Made-up ground over heavy clay	3 200	3 100	32	18	12·5	9·6	26	—	—	—	—	—	
Riding Mill ..	Sandy gravel	37 000	47 000	370	175	160	145	6	—	—	—	—	—	
Anick Grange ..	Not known	21 000	14 000	207	100	64	44	9	—	—	—	—	—	Mean of two results
Pelaw Grange ..	Made-up ground over blue clay	4 300	2 100	43	17·3	10	6·5	4	—	—	—	—	—	Total driving time for 24 ft. = 18 min.
				15 ft. 4·8	*18 ft.* 3·7	*21 ft.* 3·1	*24 ft.* 2·8							Minimum average resistivity = 1 650 ohm-cm.

average to 12 ft. was 14 000 (the actual resistivity change with depth would be appreciably greater than this), and as a result the resistance of the electrode at 12 ft. was less than a quarter of the value at 3 ft. A greater variation existed at Pelaw Grange, where the average resistivity at 12 ft. was less than half the value at 3 ft., and as a result the electrode resistance fell from 43 ohms to 6·5 ohms at 12 ft., and to 2·8 ohms at 24 ft.—a particularly satisfactory result.

Where a substratum of hard high-resistivity material such as limestone or igneous rocks exists, it is preferable to drive the electrode in an inclined direction rather than vertically, and this was done, using an inclination of 30° to the horizontal, at four of the sites. By comparison of the results shown in the Table, it will be seen that driving in this way gave approximately the same resistances as driving vertically. This would not, of course, apply to a site where there was a marked variation of resistivity with depth.

A further deep-driving experiment was conducted at Cheshunt, Hertfordshire, where a gravelly soil overlays clay located at a depth of about 5 ft. The results at 3-ft. intervals were as follows:

Length, in feet ..	1	4	7	10	13	15½
Resistance, in ohms	275	152	43	9·7	5	3·8

Conductance curves for these and four other results are shown in Fig. 3, from which it will be seen that in the final condition in all the cases except that of Pelaw Grange the conductance per unit length, i.e. the efficiency of the electrodes, is increasing. (The curves show total conductance; the conductance per unit length is the ratio of the ordinate to the abscissa.) At Pelaw Grange it starts to fall off slightly after 20 ft. When the soil has a uniform resistivity the efficiency actually falls continuously (as shown by the curve), and theoretically, therefore, the electrodes could have been driven deeper, but there are often practical objections to this. The maximum conductance occurred at Cheshunt, and had a value of 0·17 mho per foot at a depth of 16 ft. This corresponds to a mean resistivity of about 1 600 ohm-cm. As the mean resistivity to a depth of 8 ft. was about 6 000 ohm-cm., this indicates that after driving for 8 ft. the electrode penetrated into a soil of very low resistivity. At Colchester the change of strata occurred at about 24 ft. (in one case), up to which depth the mean resistivity was 15 000 ohm-cm.; at 34 ft. the mean value for the whole depth was 2 000 ohm-cm. The clay stratum responsible for this therefore had a resistivity of considerably less than 1 000 ohm-cm.—a very useful value for earthing purposes.

(ii) Plates.

Earth plates in Great Britain are rapidly being replaced in favour by driven rods or pipes. On the Continent they are still quite widely used, but they are less common in the U.S.A. The material employed is generally cast iron or copper, though lead is used in some circumstances by the G.P.O., and mild steel and "Armco" iron are sometimes employed. In soil the longest life is attained by lead or copper, and the latter has the advantage that dissimilar metal corrosion does not occur at the connection. Coke should not be used with copper plates. The

earth resistance of plate electrodes is given in an E.R.A. report* and elsewhere;† it varies with the size of plate, its depth of burial and the type of soil. Where the resistivity is 1 000 ohm-cm., a 3-ft. square plate has a resistance of about 3 ohms when buried on edge with its centre 3 ft. below the surface. At 6 ft. below the surface the resistance only falls to about 2·7 ohms. A 6-ft. square plate has a resistance of about 1·5 ohms when its centre is 5 ft. below the surface. These values may be compared with a resistance of 3·5 ohms for a 12 ft. × $\frac{1}{2}$ in. dia. copper rod, which may be installed at a much smaller cost than an earth plate of similar resistance, and has the added advantage of having the connection available for inspection.

(iii) Strips and conductors.

These electrodes, if in the form of strip, are usually made from copper having a section of not less than 1 in. × $\frac{1}{16}$ in., which is preferably untinned. The resistance of such an electrode is given by the following formula:

$$R = \frac{\rho}{250l} \cdot \log_{10} \frac{216l^2}{wt}$$

where R = resistance, in ohms.
ρ = soil resistivity, in ohm-cm.
l = length of electrode, in yards.
t = depth of burial, in feet.
w = width of strip, in inches.

If a bare round copper conductor composed of solid or stranded wires, such as is used for rural overhead lines, is employed instead of copper strip, it is necessary to replace w in the formula by $2d$, where d is the diameter of the conductor. If d is expressed in inches, l in yards, t in feet, and ρ in ohm-cm., the formula becomes

$$R = \frac{\rho}{250l} \cdot \log_{10} \frac{108l^2}{dt}$$

A curve suitable for conductor or strip electrodes is shown in Fig. 4. The effect of conductor size is extremely small within the range normally used for rural distribution, and the variation with depth of burial between the minimum permissible on account of cultivation—about 18 in.—and the maximum to which anyone would be disposed to bury an electrode—say 3 ft.—is only about 5 per cent.

Electrodes of this type may vary in size from a 10-ft. strip at the base of a rural pole-mounted transformer substation to the 62 miles of No. 14 S.W.G. copper wire used to provide the earthing system for the G.P.O. radio station at Rugby. Possibly the most extensive conductor electrode system is that provided for the 275-kV Boulder Dam line in America; 227 miles of this line are provided with four parallel $\frac{1}{2}$-in. dia. copper counterpoise conductors which interconnect all the tower footings. Other sections of the line, about 40 miles long, have two similar counterpoises, and the same size of wire was used for earthing mats at substations. In all, 1 350 miles of wire were used as earth electrodes in connection with the Boulder Dam line.

The continuous counterpoise is only necessary where the soil resistivity is high and where lightning storms are frequent. None is at present installed in Great Britain, and it is unlikely that they will be required to any large extent, although they could be employed to advantage in many parts of the Empire. There is, nevertheless, considerable scope for reducing the earth resistance of rural substations, and one large British supply undertaking has adopted conductor earth electrodes for all such cases.

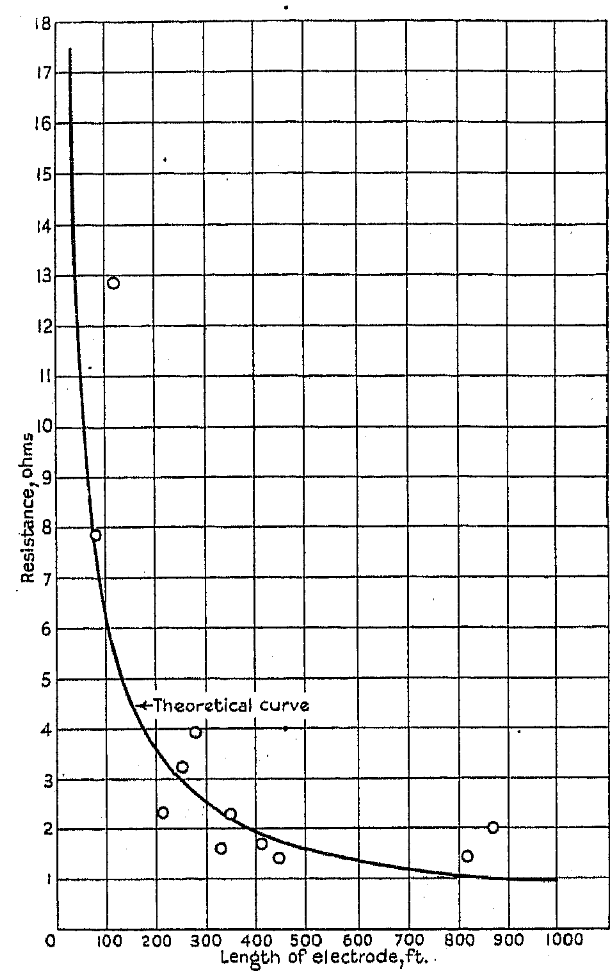

Fig. 4.—Curve showing variation of earth resistance of strip or conductor with length, for resistivity of 10 000 ohm-cm.

○ Values of resistance determined from actual measurements on strips, corrected to ρ = 10 000 ohm-cm.

(iv) Coke electrodes.

An appreciation of the true function of coke surrounding an electrode—namely, that it virtually increases the size of the electrode to that of the coke bed—led logically to the introduction of what has been called the "coke electrode," in which the size of the metal electrode has been reduced to the minimum and the proportion of coke to metal is far higher than in the more common "coke-treated electrode." The two types should not be confused.

The coke electrode may take several forms; it may consist of a trench partially filled with coke breeze, a bore-hole filled for several feet, or a horizontal bed of breeze, say 3 in. to 1 ft. thick. In each case connection is made by a metal plate or rod of relatively small size. The resistivity of coke breeze is usually so small compared with that of soil that the resistance between the metal electrode and the surface of the coke and soil is very small compared with the resistance in the soil itself. The advantages of such an electrode are:

* P. D. MORGAN and H. G. TAYLOR: "The Resistance of Earth Electrodes," E.R.A. Report Ref. F/T50.
† P. J. HIGGS: *Journal I.E.E.*, 1930, **68**, p. 736.

(i) Exceptionally long life.
(ii) Contact with the soil is maintained in all weather conditions.
(iii) Cheapness in certain cases, and particularly when the electrode can be installed at the same time as the foundations of the substation.

The disadvantages are:

(i) For equal cost a lower resistance may be obtained by using driven pipes or rods.
(ii) There is a possibility of a resistance film of oxide forming between the iron and the coke. Very little is known about this at present, but there is some evidence of its taking place with a mild steel electrode.

Further details about coke electrodes will be found in E.R.A. Report Ref. F/T14.

(b) Spacing of Electrodes

Since the earth resistance of an electrode is in the soil itself, it follows that if two are driven too close together their resistance areas will overlap, and the net resistance

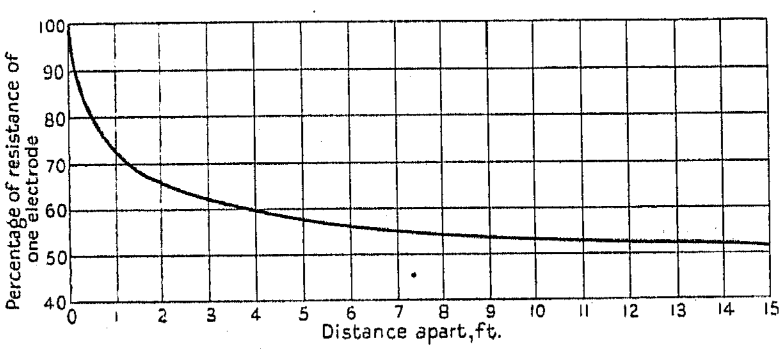

Fig. 5.—Variation of earth resistance with distance apart of two 1-in. dia. tube or rod electrodes connected in parallel.

of the two in parallel will not be as small as if they were well separated from each other. This effect is shown in Fig. 5, where the resistance of two 1-in. diameter electrodes is plotted against their distance apart. The larger the diameter of the electrode, the greater the spacing required for a given percentage reduction of resistance, though for driven electrodes the variation is negligible; it is important, however, with plates or large pipes when buried and surrounded by coke. Conductor electrodes should radiate from a point or, if in parallel lines, should be several yards apart. Plates should never be less than 6 ft. from one another.

(c) Effect of Soil Resistivity

The resistance of any earth electrode depends directly on the soil resistivity, and this is principally determined by the amount and characteristics of the electrolytes present in the soil; if any soil is completely dried out it has such a high resistivity as to render it quite useless for earthing. The resistivity of the moisture in the soil is determined (*a*) by the nature of the soluble salts present, which depends principally on the locality, but may be affected by drainage of salts from other places; (*b*) by the concentration of the salts, which depends on the rainfall, permeability of the soil, evaporation and rate of removal of moisture by vegetation; (*c*) by the temperature, since electrolytes have a temperature coefficient of resistivity of about -2% per deg. C.; and (*d*) by the bacteriological activity in the soil, which is dependent on the time of year and is affected by the nature and degree of vegetation.

Lowest resistivity is found in salt marshes, and low values are sometimes obtained in made-up ground containing refuse, ashes, cinders, etc. Next come certain clay soils, of which low-lying London clay is a good example; here values of resistivity as low as 500 ohm-cm. may be obtained. Unfortunately clays are not consistent, and occasionally hard, relatively dry clays are found which have a resistivity as high as 15 000 ohm-cm. In the same class with clays are loams and sandy clays, which may range in resistivity from 1 000 ohm-cm. up to 15 000 ohm-cm., or even more with dry loam. The latter is not often used for earthing, since it is essentially a surface soil, and electrodes may normally be expected to be buried below it. As the sand or gravel content of soil increases the resistivity increases, and anything approaching a pure sand or gravel may be regarded as a particularly bad soil for earthing. In certain cases it may be suitable, but, on the other hand, the resistivity may even approach 1 000 000 ohm-cm., and it should therefore always be viewed with suspicion and tests made before any earthing is carried out. A very deceptive type of soil is that met in mountainous districts; it may be very wet—even marshy—and yet may have a resistivity of the order of 20 000 ohm-cm. It is generally assumed that this is due to the absence of soluble salts, which is confirmed by the known purity of mountain streams. Possibly excessive rainfall rapidly washes away salts which in other soils would be present in greater concentration owing to the smaller rainfall. Absence of vegetation may also have some influence. It is in such soils that evidence has been obtained of the effect of vegetation and possibly of bacteriological activity. At an E.R.A. test site in North Wales the rainfall is about 85 in. per annum; in winter the site is boggy; in summer it is never dry, though very different from its winter condition. The vegetation is very sparse. The resistivity variation is very small, being little more than 10 % on either side of a mean value over a period of 5 years, but the change is a periodic one, the resistance always being a maximum in the winter and a minimum in the summer (see Fig. 6). It is assumed that this is due partly to temperature changes and partly to the effect of vegetation and bacteriological activity, which is highest in the summer and results in the acidification of soil.

Any soils of a calcareous or rocky nature have a high resistivity, and wherever possible the superficial layer of soil should be used for earthing. This has certain drawbacks, such as the risk of freezing, which increases soil resistivity enormously; and the danger of surface voltage-gradients, under fault conditions, which diminish in intensity as the depth of burial of the electrode increases. It is relatively useless, however, to try to earth in chalk, limestone and other such materials unless one is prepared to excavate a trench and use large quantities of coke. The cheapest method is to bury conductor or strip electrodes, or to drive long, small-diameter rods at a small inclination to the horizontal, so that only the surface soil is used.

Data are given in Appendix 2 showing the results of actual resistivity measurements on various soils. It will be clear from these that very large variations exist in any one soil, but this will be understood when it is remembered that one of the dominating factors is the electrolyte present—this is almost as important as the type of soil, though naturally the type of soil often determines the conductivity of the electrolyte. It is important not to place too much reliance on tabulated figures of resistivity; it is much better to make a rough test on the site. If a four-terminal earth tester is not available for doing this, a trial rod electrode should be

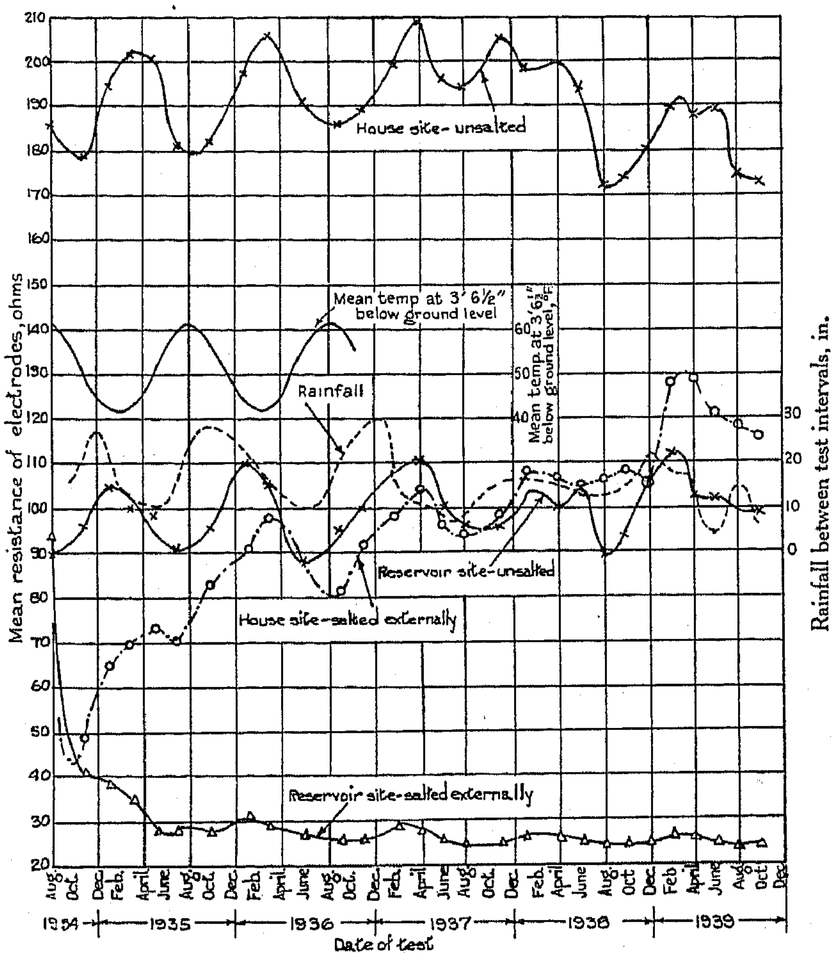

Fig. 6.—Seasonal change of resistance of 6-ft. pipe electrodes in peat in N. Wales.

installed and the resistivity determined by substitution of the appropriate values in the usual formula

$$R = \frac{\rho}{2\pi L} \cdot \log_e \frac{4L}{d}$$

(d) Artificial Treatment

(i) Salting.

Reduction of resistance.—In order to determine the reduction of resistance effected by salting, and the frequency with which it is necessary to re-salt electrodes, tests have been in progress for a number of years at five different sites where various extremes of soil conditions and rainfall exist. The principal sites were as follows:

(i) Alperton (Middlesex). Impervious London clay with a low rainfall (about 20 in. per annum).

(ii) Newchurch Common, Northwich (Cheshire). Pervious sand with an average rainfall (about 36 in. per annum).

(iii) Eigiau (North Wales). Peat with a high rainfall (about 85 in. per annum). At this place two adjacent sites were selected—one on sloping ground where the salt would tend to be very rapidly washed away (known as the "House" site), and one on flat, boggy ground (known as the "Reservoir" site).

In addition, two other sites were available, viz. Cuffley and Stevenage, where a few electrodes had been installed and salted when the tests were commenced on the use of coke for reducing resistance. At these two sites—the former consisting of London clay with some loamy gravel at the surface, and the latter of chalk—the rainfall is much the same as for London, and tests have been in progress for 7 and 6 years respectively. At North Wales and Northwich tests have been in progress for 5 years, and at Alperton for $4\frac{1}{2}$ years. The results of these tests, together with the details of others on the use of coke (which is referred to in a later section), are given in Table 4. Fig. 7 shows the changes of resistance of the electrodes at Cuffley over the whole period of test. The resistances of the salted pipes steadily decreased from December, 1932, to October, 1936; since then the increase has been very slight, and the resistance is now at about 25 % of the initial value. During the period of the tests the resistance value for an unsalted pipe increased at one time to 170 % of its initial value, but the conditions which produced such an effect had no appreciable influence on the salted electrodes. There is no direct relationship with the rainfall—only long-period changes show any connection. This is the most striking case of the durability of salting—after more than six years the resistance is still less than 25 % of the initial value before salting. The resistances of the untreated pipes are much the same as when the pipes were first installed.

The electrodes at Stevenage were installed when the soil resistivity was high and increasing. In consequence the resistance values of the majority of electrodes, after rising to a maximum during the next twelve months, steadily dropped for the following two years—the minimum in most cases being reached in July, 1936. One salted pipe fell by 90 % and the other by 82 % from its initial value, but this must have been partly due to the general reduction of resistivity, since the unsalted pipes fell by 77 % and 30 % in the same period. The pipe salted internally fell by 70 % and has now returned to its initial value. The mean resistance of the two pipes salted externally is about 35 % of their initial value. One unsalted pipe stands at 35 % and another at 65 %. Chalk is a very difficult soil in which to obtain reliable results, since, when driving electrodes, fissures are formed in the ground which are only slowly refilled and give rise to erratic resistances. The salted plate at this site had an initial resistance *after* salting of 18 ohms as compared with 108 ohms for an unsalted plate; its minimum resistance was about 10 ohms, which occurred nearly three years later. At this time the resistance of the unsalted plate was 54 ohms. The resistances have now changed to about 26 ohms and 43 ohms respectively. As the resistance of the plate could not be measured before salting, it is difficult to assess with certainty the value of the salting, but at least it seems to have been effective over a period of about three years.

Table 4

SEASONAL CHANGE OF RESISTANCE OF ELECTRODES, AND EFFECT OF SALT AND COKE TREATMENT

Site and date of installation	Type of soil	Duration of test	Description of electrode: Type	Description of electrode: Size	Treatment of soil	Earth resistance of electrodes, ohms: Initial	Average	Max.	Min.	Max./Min.	Remarks
		years									
Cuffley (Herts) Electrodes installed in Aug., 1932	Loamy gravel over London clay	2	Strip	10 ft. × 1 in. × 1/16 in.	Coke	1·40	—	—	1·00	—	Electrodes corroded away after about 2 years
		2	Strip	20 ft. × 1 in. × 1/16 in.	Coke	1·20	—	—	1·00	—	
		2	Strip	30 ft. × 1 in. × 1/16 in.	Coke	1·20	—	—	1·00	—	
		4	Strip	10 ft. × 1 in. × 1/16 in.	—	3·1	4·6	7·4	3·1	2·4	
		7	Strip	20 ft. × 1 in. × 1/16 in.	—	1·50	2·24	3·8	1·40	2·7	
		7	Strip	30 ft. × 1 in. × 1/16 in.	—	2·40	2·73	4·3	2·03	2·1	
		7	Plate	2 ft. × 1½ ft. C.I.	Coke	1·20	1·43	1·72	1·15	1·5	
		7	Plate	2 ft. × 1½ ft. C.I.	—	3·5	5·6	9·8	3·2	3·1	
		7	Pipe	6 ft. × 1¼ in. dia.	Coke	2·30	4·7	12·5	2·30	5·4	
		7	Pipe	6 ft. × 1¼ in. dia.	—	6·2	7·6	10·4	6·1	1·7	
		7	Pipe	6 ft. × 1¼ in. dia.*	—	10·0	12·4	15·0	8·1	1·8	The ratio max./min. may have been 4·2; a defective clip made results in 1933–34 indefinite
		6½	Pipe	6 ft. × 1¼ in. dia.	Salted	12·9	—	12·9	1·71	7·5	Final resistance = 2·4 Ω
		6½	Pipe	6 ft. × 1¼ in. dia.	Salted	27·0	—	27·0	3·8	7·1	Final resistance = 6·5 Ω
Stevenage (Herts) Electrodes installed in Nov., 1933	Chalk	6	Strip	10 ft. × 1 in. × 1/16 in.	Coke	20·2	18·4	21·9	12·7	1·7	
		6	Strip	30 ft. × 1 in. × 1/16 in.	Coke	9·0	8·8	10·0	6·4	1·6	
		6	Strip	10 ft. × 1 in. × 1/16 in.	—	52	40	58	23·3	2·5	
		6	Strip	30 ft. × 1 in. × 1/16 in.	—	32	20·7	40	9·3	4·3	
		6	Plate	3 ft. × 3 ft. C.I.	Coke	24·0	21·4	25·8	15·6	1·7	
		6	Plate	3 ft. × 3 ft. C.I.	Salted	18·0†	—	29·6	9·8	3·0	Final resistance = 25·9 Ω
		6	Plate	3 ft. × 3 ft. C.I.	—	108	75	120	44	2·7	
		6	Plate	3 ft. × 3 ft. M.S.	—	63	54	69	38	1·8	Expanded-metal plate; horizontal
		6	Plate	3 ft. × 3 ft. M.S.	—	95	82	116	54	2·2	Expanded-metal late; vertical
		6	Pipe	6 ft. × 1¼ in. dia.	—	269	176	370	62	6·0	
		6	Pipe	6 ft. × 1¼ in. dia.	—	71	77	118	48	2·5	
		6	Pipe	6 ft. × 1¼ in. dia.	Coke	23·0	19·3	28·3	12·9	2·2	
		6	Pipe	6 ft. × 1¼ in. dia.	Salted	64	—	74	11·0	6·7	Final resistance = 23·5 Ω
		6	Pipe	6 ft. × 1¼ in. dia.	Salted	117	—	117	11·5	10·2	Final resistance = 40 Ω
		6	Pipe	6 ft. × 2½ in. dia.	Salted internally	53	—	63	16·0	3·9	Final resistance = 50 Ω
Riding Mill (Northumberland) Electrodes installed in Jan., 1933	Sandy Gravel	4	Strip	10 ft. × 1 in. × 1/16 in.	Coke	52	45	52	40	1·3	
		4	Strip	30 ft. × 1 in. × 1/16 in.	Coke	30	26	34·5	21·8	1·6	
		4	Strip	10 ft. × 1 in. × 1/16 in.	—	111	148	200	111	1·8	
		4	Strip	30 ft. × 1 in. × 1/16 in.	—	65	80	172	58·5	3·0	
		4	Plate	3 ft. × 3 ft. C.I.	Coke	48	46	52	41	1·3	
		4	Plate	3 ft. × 3 ft. C.I.	—	100	99	105	90	1·2	
		4	Pipe	6 ft. × 1¼ in. dia.	Coke	70	64	70	57	1·2	
		4	Pipe	6 ft. × 1¼ in. dia.	—	225	214	258	169	1·5	
		4	Pipe	6 ft. × 1¼ in. dia.*	—	212	196	256	166	1·5	Buried pipe

Site and date of installation	Type of soil	Duration of test	Type	Size	Treatment of soil	Initial	Average	Max.	Min.	‡	Final resistance of electrodes	Number of pipes used for tests
											ohms	
Eigiau-Reservoir site (N. Wales) Aug., 1934	Peat	5	Pipe	6 ft. × 1¼ in. dia.	—	89·5	100	112	88	1·4	99	7
		5	Pipe	6 ft. × 1¼ in. dia.	Salted	94	—	94	24	4·8	24·4	5
		5	Pipe	6 ft. × 1¼ in. dia.	Salted internally	93·5	—	93·5	43	2·4	67·5	1
Eigiau-House site (N. Wales) Aug., 1934	Peat and rock	5	Pipe	6 ft. × 1¼ in. dia.	—	186	190	209	172	1·7	173	9
		5	Pipe	6 ft. × 1¼ in. dia.	Salted	136	—	136	43	5·1	116	5
		5	Pipe	6 ft. × 1¼ in. dia.	Salted internally	167	—	169	92	2·5	144	3
Newchurch Common (Cheshire) Aug., 1934	Sand	5	Pipe	6 ft. × 1¼ in. dia.	—	1 230	1 780	2 790	1 180	2·4	2 730	7
		5	Pipe	6 ft. × 1¼ in. dia.	Salted	712†	—	1 810	152	14·1	1 810	5
		5	Pipe	6 ft. × 1¼ in. dia.	Salted internally	703†	—	1 410	427	2·4	1 340	3
Alperton (Middx.) April, 1935	London clay	4½	Pipe	6 ft. × 1¼ in. dia.	—	3·7	4·2	5·7	3·2	2·4	4·5	5
		4½	Pipe	6 ft. × 1¼ in. dia.	Salted	2·38	—	3·3	1·87	2·3	1·97	5
		4½	Pipe	6 ft. × 1¼ in. dia.	Salted internally	4·0	—	6·1	3·1	3·3	6·1	3

NOTES TO TABLE.—1. All pipes were galvanized mild-steel water tubes, 1 in. bore × 1¼ in. outside diameter.
2. All plates except one (of expanded metal) were buried vertically with the top edge 3 ft. below the surface.
3. All strips were copper—three at Riding Mill plain and the others tinned; they were buried at 2 ft. 6 in. below the surface.
4. Pipes salted internally were treated with brine or dry salt about four times at 2-monthly intervals; these pipes have about 20 small holes drilled in them and have solid points.
5. Externally-salted pipes were treated once with 1 cwt. of salt inserted in a 4-ft. dia. hemispherical hole around the top of the pipe.

* These pipes were buried; all others in soil were driven. † This resistance was measured after salting.
‡ The values below here are the largest ratios of maximum to minimum for any single pipe.

The results of the tests in N. Wales are shown in Fig. 6. It will be observed that at the Reservoir site the externally salted electrodes have been steadily decreasing in resistance since the commencement of the tests; on the other hand, those salted internally reached a minimum after about 18 months and have been increasing since. Their resistance now is about 68 % of that of the unsalted ones, whereas that of the externally salted ones is about 25 %. At the House site the minimum resistance of those salted internally was about 50 % of that of the unsalted ones, and is now back to about 83 %. On the other hand, those salted externally immediately dropped to 20 %, but then continuously increased, and are now at about 67 %. There is considerable variation at this site, and two electrodes, which are practically in small streams, returned to their original resistance in a very short time. One started at 186 ohms, fell to 45 ohms the next day, was back to 110 ohms in three months, 170 ohms in five months, and 185 ohms in seven months. The other was 66 ohms immediately after salting, 32 ohms the next day, 35 ohms two months later, and then 48, 62, 74, 72, 92, 100, and 112 at successive intervals of two months. The rapid removal of the salt in these two cases adversely affects the average result, though the other three salted electrodes reached their minimum in less than twelve months, and have since been increasing in resistance. The two electrodes referred to above were deliberately placed in situations where the salt was likely to be quickly washed away, and the whole site is in such a locality as to encourage quick removal; nevertheless, it is significant to note that after 5 years the resistance is still only 67 % of that of the unsalted pipes. The reduction of resistance is, however, not as large as was expected.

The results for Newchurch Common, Northwich, Cheshire, where the soil is mainly sand, are shown in Fig. 8. Here the reduction of resistance was considerably greater than in North Wales, values of resistance for the salted electrodes as low as 7 % of the resistance of the unsalted ones being obtained. For the electrodes salted internally the minimum value was 25 %. These minima occurred at about eight months after installation, and since then there has been a steady increase of resistance, until now—5 years after the start—the electrodes salted internally have a resistance 49 % of that of the unsalted ones, and those salted externally have risen to 66 %.

At Alperton the soil resistivity is unusually low (of the order of 500 ohm-cm.), and, owing partly to this and partly to the impervious nature of the soil, it is difficult

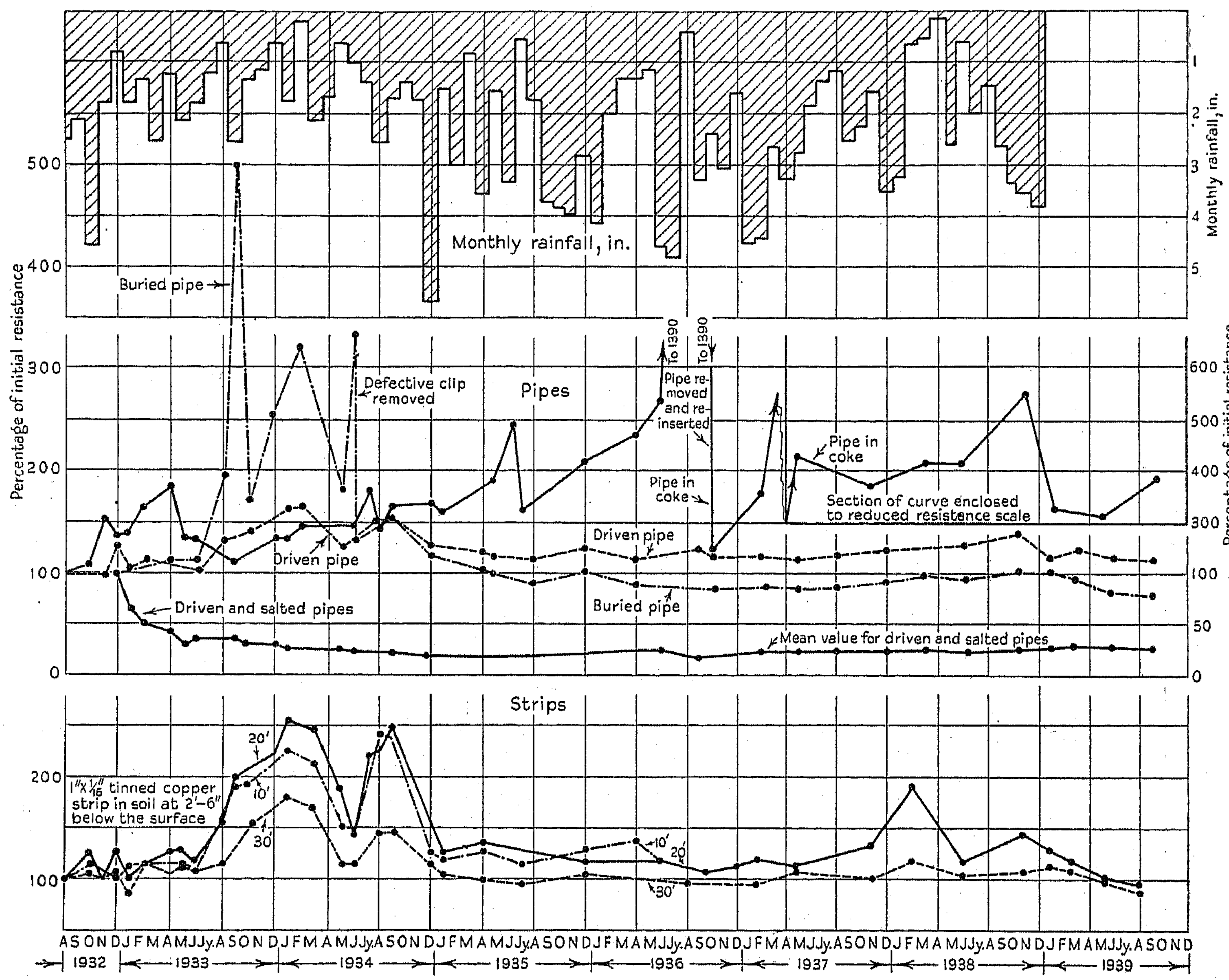

Fig. 7.—Seasonal variation of resistance of strip and pipe electrodes at Cuffley.

to effect a large reduction of resistance by salting. The results show that whilst the reduction is only about 55 % when the salt is externally applied, this reduction has remained constant over a period of three years. Applied internally, there was little reduction of resistance, and within two years the resistance was back to the normal value.

The salting of soil is a process which occurs naturally in certain parts of the world, and knowledge of its characteristics has a bearing on the artificial treatment of earth electrodes. In arid areas where the evaporation is very high the soil tends to acquire an increasing salt content. When the salt concentration reaches a certain value deflocculation occurs, and the soil then becomes almost impervious to water and remains moist and sticky. Attempts to irrigate such land have proved quite useless, since the water does not flow through and carry the salt with it, but lies on the surface until it evaporates. This effect can readily be illustrated in the laboratory, and a test was made on London clay which effectively illustrated the phenomenon. Two funnels were filled with clay, and one washed with distilled water and the other with an equal quantity of salt water. Subsequently distilled water could be readily filtered through the untreated soil, but practically none would flow through the funnel of clay which had been washed with salt water. Water was left standing on the surface and remained so until it evaporated away after some weeks.

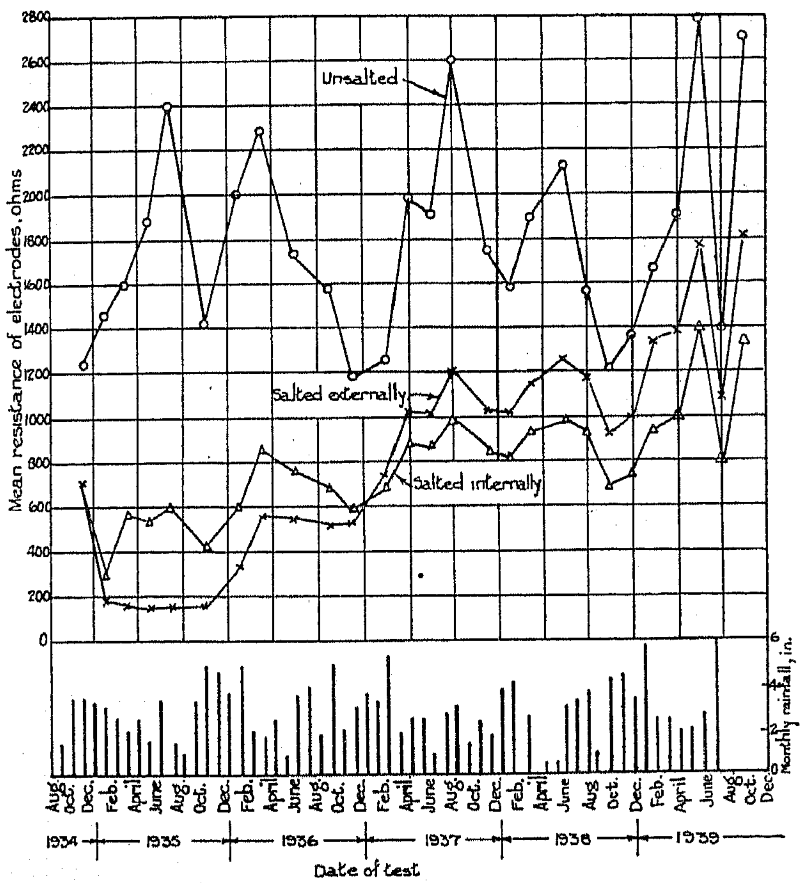

Fig. 8.—Seasonal change of resistance of electrodes in sand at Newchurch Common.

This simple experiment explains why the salting of soil is in many cases of such lasting advantage. In practically all the tests the effect of the salt is still obvious after several years, and in favourable cases it is clear that the beneficial effect will be retained for a period of well over five years.

The tests show that changes due to salting take place slowly, and in some instances it is a matter of years before the resistance reaches a minimum value. The return to normal occurs at a variable rate, being high in pervious soils and low in impervious ones, and in most cases the tests have not yet proceeded for a sufficient length of time for the return rate to be properly judged. Most of the electrodes have passed their minimum resistance, though the electrodes which have been installed for 5 years at the Reservoir site in North Wales are an exception.

Tests have been in progress at Cuffley for four years to find whether the grading of salt had any effect on resistivity, but although the grade ranged from common cooking salt to 3-in. diameter lumps of rock salt no appreciable variation in resistance or rate of change of resistance could be detected.

Corrosion.—Whilst salting reduces the resistance of earth electrodes, it is generally recognized that it increases the rate of corrosion. To find the importance of this an extensive survey is being made covering soils of various types, in which specimens of different metals commonly used for earth electrodes have been buried. The full investigation has been planned over a period of five years, and results have now been obtained for the first two, and in some cases three, years. Twelve sites were selected, having soils representative of those most commonly found in this country where earthing is required. The results are shown in Table 5.

The metals chosen for the investigation as being most generally used for earth electrodes were Armco iron, mild steel, galvanized mild steel, cast iron, copper and tinned copper.

A number of specimens of each metal were obtained, measuring 6 in. × 1 in. × ⅛ in., and were weighed. In each soil two adjacent sites were chosen measuring about 6 ft. square, and were excavated to a depth of about 2 ft. 6 in. Twenty specimens of each metal were placed in each excavation, parallel to one another and spaced about 2 in. apart. About 6 in. separated the specimens of one metal from those of the next. One of the excavations was then refilled with the natural soil, and before the soil was returned to the other about 1 cwt. of salt was mixed with it.

After a period of about a year, four specimens of each metal were recovered from the natural and salted soil at each site, and the loss in weight determined. This procedure regarding recovery and examination of specimens was repeated after a further period of about a year, and will be continued at similar intervals until the whole of the specimens have been recovered.

The results to date show that copper, whether plain or tinned, is the best of the metals investigated from the point of view of resistance to corrosion.* At none of the sites at which the tests are being carried out was the corrosion of either of these metals in excess of 1 % in the natural soil, or 1·5 % in the salted soil, in the first two or three years; while in most cases it was less than

* This is confirmed by extensive tests which have been carried out over a long period by the U.S. Bureau of Standards. For further details see "The Resistance of Copper to Soil Corrosion" (a Copper Development Association publication).

0·5 %. The corresponding figures for galvanized mild steel, which is the next best corrosion-resisting metal, are 2 % in natural and 2·5 % in salted soil.* The effect of salting on this metal is, however, very marked in chalk, where the corrosion in salted soil is 8 to 20 times that in the natural soil. The unprotected ferrous metals offer in general far less resistance to corrosion than galvanized steel or the non-ferrous metals, and the effect of soil type and of salting is more marked.

In Table 5 the soils are roughly classified according to the effect of salting on the non-protected ferrous metals, i.e. mild steel, Armco iron and cast iron. The approximate mean values of the corrosion rates in natural soils are also given.

Table 5

EFFECT OF TYPE OF SOIL ON CORROSION RATE OF ARMCO IRON, MILD STEEL AND CAST IRON

Soil	Site	Approximate values of corrosion in natural soil, %			Range of ratio of corrosion in salted soil to corrosion in natural soil
		1st year	2nd year	3rd year	
Chalk	Stevenage (Herts)	< 1	< 1	1	6 to 20
Jurassic limestone	Chipping Norton (Oxon)	< 1	< 1	—	
Chalky boulder clay	Cherry Green (Herts)	1	$1–2\frac{1}{2}$	—	3 to 7
Sandy loam	Teddington (Middlesex)	$1\frac{1}{2}–3\frac{1}{2}$	$1\frac{1}{2}–3\frac{1}{2}$	—	
Gravel	Hertford	$1\frac{1}{2}$	2	2	2 to 5
Shale over coal measures	New Ridley (Northumberland)	$1\frac{1}{2}–3$	—	3–6	
Clay with flints	Preston (Herts)	$1\frac{1}{2}$	3	—	1 to 3
London clay	Alperton (Middlesex)	< 1	2	5	
Boulder clay	New Ridley (Northumberland)	$1\frac{1}{2}$	—	$3\frac{1}{2}–4$	1 to 2
Bunter sandstone	Eddisbury (Cheshire)	$2\frac{1}{2}$	$3–5\frac{1}{2}$	$3\frac{1}{2}–5\frac{1}{2}$	
Keuper marl	Eddisbury (Cheshire)	< 1	< 1	$1\frac{1}{2}–3$	1 to 1·5
Oxford clay	Stewartby (Beds)	< 1	$1\frac{1}{2}–3$	—	0·5 to 1

(ii) Coke.

Extensive tests on the use of coke for reducing the resistance of earth electrodes have been conducted at Stevenage, Cuffley, and Riding Mill (Northumberland), with the results shown in Table 4 and Fig. 7 (Cuffley only).

The tests have been extended over a period of seven years, and the conclusions reached are set out below in the form of advantages and disadvantages of using coke.† Whether coke is used or not in any particular case will depend on the importance attached to the various points. The question of cost and probable life will also have a bearing on the choice.

Advantages.

(i) The addition of coke breeze having a resistivity small compared with that of the soil, to a distance of 9 in. all round electrodes, effects the following reductions in resistance:—*

Strips—about 50 % to 75 %, depending on the size of electrode and type of soil.
Pipes—about 50 %.
Plates—about 50 %.

(ii) The seasonal variation of resistance is generally less when the electrodes are surrounded with coke breeze than when they are inserted direct in the soil.

(iii) The current loading capacity is increased.

Disadvantages.

(i) The cost of the electrode is higher owing to the larger hole which it may be necessary to excavate, and on account of the cost of the coke breeze.

(ii) For equal cost a much lower resistance may be obtained by using driven pipes or rods.

(iii) The life of electrodes in coke is less than that of electrodes in soil—some types of coke being particularly liable to cause corrosion.

(iv) The rusting of an iron electrode causes a much greater percentage increase of resistance in coke than in soil.

(v) Because the coke bed itself acts as an electrode, corroding-away of the metal plate or strip may not result in a large increase of resistance, but the current loading capacity of such an electrode may be considerably reduced. Such a situation creates a false sense of security.

(vi) Electrodes surrounded with coke are cathodic and give rise to direct currents when connected in parallel with such electrodes as water pipes, lead cable-

* It should be noted that at this stage of the tests the galvanizing was still in satisfactory condition.

† Full details of the tests are given in E.R.A. Report Ref. F/T118.

* In determining these reductions it has been necessary to adjust the values given in Table 4 on account of resistivity variation.

sheaths, or steel frameworks, which results in the corrosion of the anodic electrode. Whether this is serious or not is not known, but tests are being made and there is ample evidence of the flow of such currents.

(vii) The use of coke usually involves a connection between the lead and the electrode which is not available for inspection—this does not apply to rods or pipes driven direct into the soil.

(e) Seasonal Variation of Resistance

The tests on the effect of coke and salt in reducing the resistance of electrodes also provided information on the seasonal variation of resistance. It is frequently stated that very large variations occur, but this has not been confirmed by the E.R.A. tests except in one particular soil—viz. chalk. Here ratios of maximum to minimum resistance of 4·3 for a strip electrode and 6·0 for a 6-ft. driven pipe were obtained over a period of six years. In all other soils over periods of the same order the variation has not exceeded about 3, and in many cases it has been less than 2.* This applies to a total of nearly 60 electrodes. The ratio of the minimum to the maximum resistance is shown diagrammatically for all the electrodes in Fig. 9. In the case of the unsalted and coke-treated electrodes this value shows the extent of the seasonal variation; in the case of the salted electrodes it indicates the reduction effected by salting. Fig. 7 shows the results of tests on some of the electrodes at Cuffley, and is particularly interesting as indicating that owing to the dry summers of 1933 and 1934 the electrodes at Cuffley attained resistances which in the majority of cases have not since been exceeded. Similar results occurred at Stevenage in chalk. An interesting feature is that the maximum resistance of the strips occurred during the *winter* of 1933–34 and a minimum was not reached till the following June.

Fig. 6 shows the seasonal variation of resistance in North Wales, and Fig. 8 that at Newchurch Common. In the case of North Wales similarity will be noted between the resistance, temperature, and rainfall variations.

The conclusions drawn from the investigations of seasonal change of resistance are as follows:—

(i) Electrodes in some soils and localities may take several years to recover from the effects of an exceptionally dry period; in other soils and situations rapid response to weather changes takes place and there is no observable long-time effect.

(ii) Over periods of test varying from four to seven years, including exceptionally dry and wet years, the maximum individual resistance variation due to variations of soil moisture was 6 to 1; one value of 4·3 to 1 occurred, and the remaining 56 values for strips, pipes, and plates in soil and in coke were all less than 3·5 to 1; at least 30 of these were less than 2 to 1.

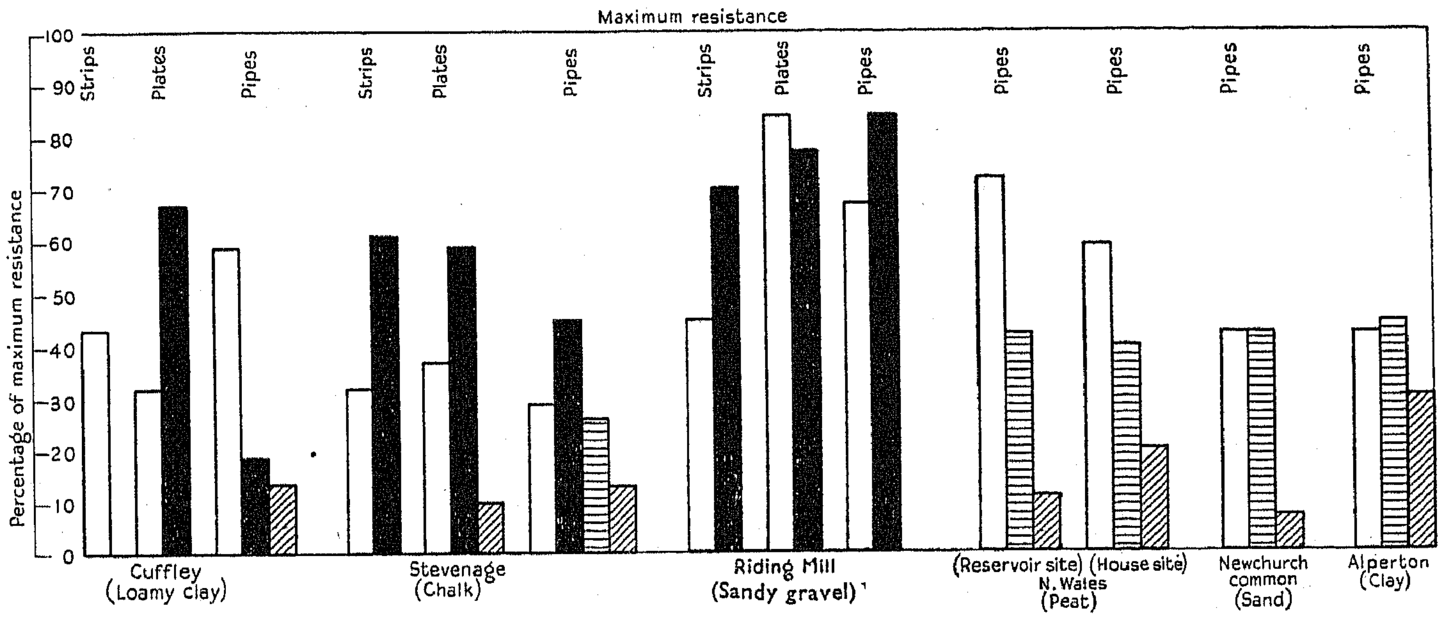

Fig. 9.—Ratio of minimum to maximum resistance of all electrodes over complete test period.

Electrodes in soil. Electrodes surrounded with coke breeze.
Pipe electrodes, salted internally. Electrodes salted externally.

(iii) There is not a great difference between the clay, gravel, and chalk at Cuffley, Riding Mill, Alperton, Newchurch Common, and Stevenage with respect to the magnitude of resistance variation, but the two high values referred to in (ii) were obtained at Stevenage, and this suggests that chalk may occasionally give values above the average.

(iv) The tests confirm the view that the deeper the electrode the less the seasonal variation of resistance, though the difference is small for the range of depth used.

(v) The resistance changes in peaty soil, characteristic of mountainous regions, are very small.

(vi) The seasonal change of resistance of salted electrodes is not generally appreciably less than that of unsalted ones.

(vii) The seasonal change of resistance of coke-treated electrodes is generally less than that of untreated ones.

(5) VOLTAGE GRADIENT AROUND EARTH ELECTRODES

When current flows to earth from an electrode a voltage gradient exists on the surface of the ground,

* A value of 5·4 for a coke-treated mild-steel pipe is thought to be due to rusting on the surface of the electrode.

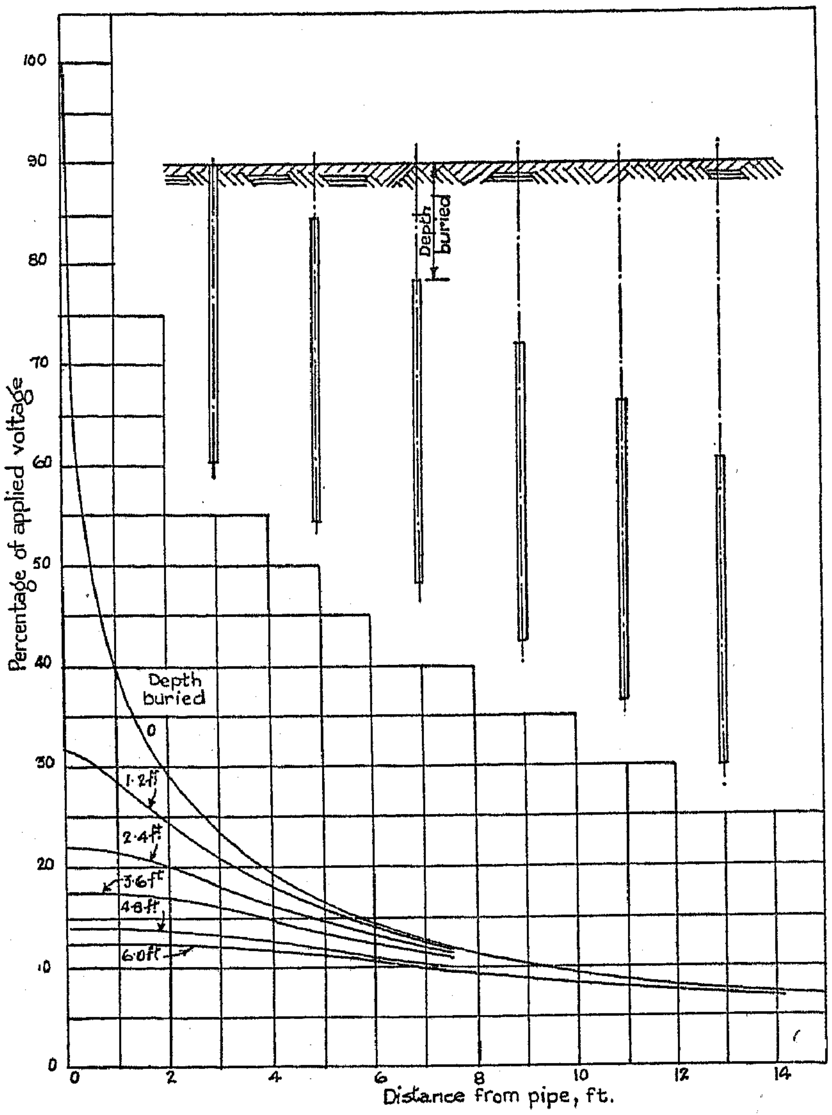

Fig. 10.—Potential on ground surface due to pipe 6 ft. long, 1 in. dia., buried vertically at various depths.

which may be undesirable for two reasons. Where the substation and the electrode system are large, incoming telephone and pilot cables may, under fault conditions, have sufficient voltage impressed between their sheath and core to cause breakdown of the insulation. This is due to the fact that the cores of such cables are substantially at earth potential. Full details relating to this problem have been published elsewhere.*

The second reason why the voltage gradient may be undesirable is that with small electrodes the rate of change of voltage on the surface of the ground may be so great as to represent a potential danger to cattle whose fore and hind feet are sufficiently separated for a shock to be experienced. Trouble from this cause occurs principally with pole-mounted transformer substations on low-voltage systems. In rural areas it is by no means uncommon for the earth-path resistance to be such that faults are not cleared within a short period, and in such cases animals, which frequently congregate near a pole, are liable to receive a dangerous shock. The same trouble sometimes occurs at farms where earth electrodes are provided for individual appliances. The principal remedies are either to bury the electrode sufficiently deeply and to make a connection to it by means of an insulated lead,† or to bury the electrode at some point inaccessible to cattle rather than at the substation.

Voltage-gradient curves have been plotted‡ for all the normal types of earth electrode in soil of uniform resistivity and soil having both high- and low-resistivity

* Paris H.T. Conference, 1935, Paper No. 322; and E.R.A. Reports Ref. F/T71 and F/T86.

† This practice has been adopted by the North-Eastern Electric Supply Co. with complete satisfaction. Two pipe electrodes have been installed at the bottom of bored holes at some 200 substations; the pipes are packed in with coke, and connection made by means of insulated leads.

‡ E.R.A. Report Ref. F/T104; and Paris H.T. Conference, 1937, Paper No. 210.

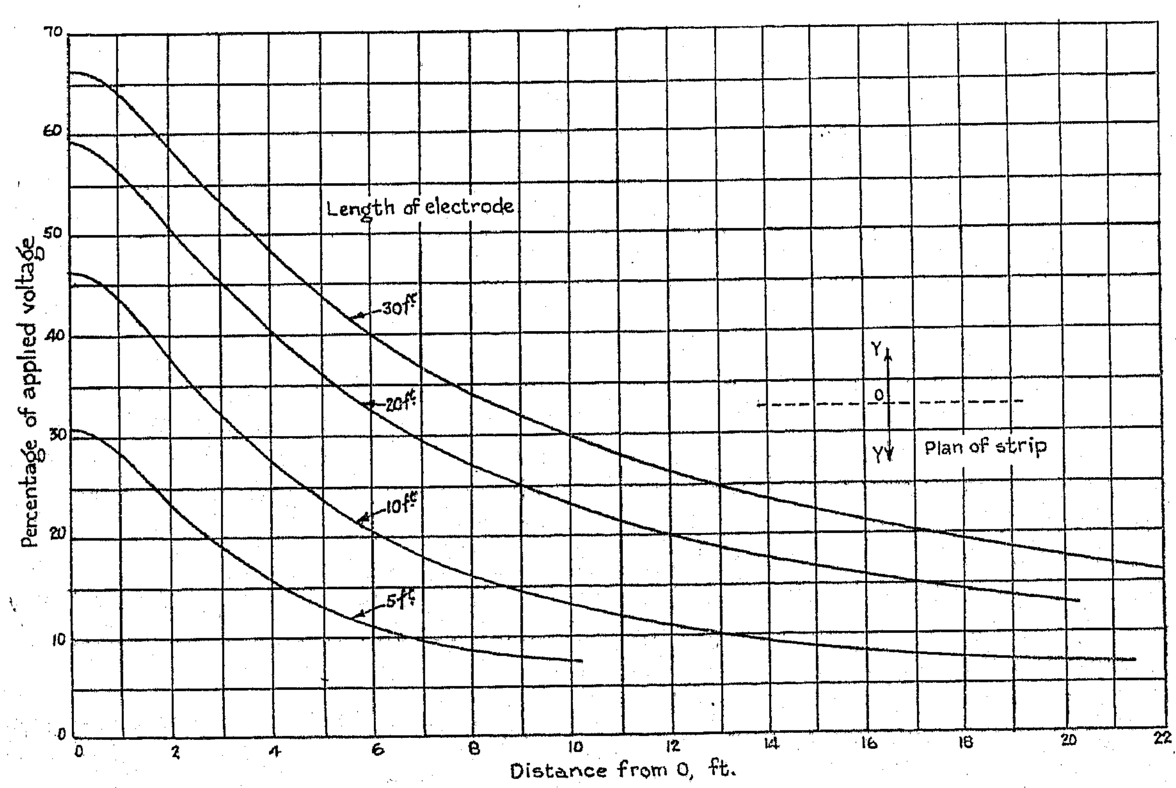

Fig. 11.—Potential on ground surface due to strips 1 in. × 0·1 in., of various lengths, buried horizontally at a depth of 2 ft. Values given are those along a line OY perpendicular to the length of the strip.

surface layers—the ratio of the resistivities in the two cases being 100 to 1. The result of this stratification is to effect an increase of gradient of not more than 50 % when the high-resistivity layer is uppermost, and then only in certain cases. When the low-resistivity layer is uppermost, the gradient is sometimes less steep than with a uniform-resistivity soil.

The advantage of driving the top end of a pipe below the surface, or of insulating the upper end of it, is shown in Fig. 10. The gradient curves for a strip electrode are shown in Fig. 11.

(6) THE LOADING CAPACITY OF EARTH ELECTRODES

An earth electrode should be designed to have the resistance required, a non-dangerous voltage gradient, and a loading capacity adequate for the system of which it forms a part. Despite the importance of this last feature, very little experimental work has previously been done on the subject, and the requirements are generally ignored in designing an earth-electrode installation. Ignorance of the behaviour of electrodes in this respect has not often given rise to trouble, but definite cases have been reported from the Canterbury Plains area of New Zealand where earth electrodes have increased in resistance so rapidly that protective gear has failed to operate. The introduction of Petersen coils is likely to bring the matter more to the front in the future, since with such devices heavy earth currents can be carried for some hours; and the general increase in the capacity of systems warrants the determination and dissemination of precise details regarding the response of earth electrodes to fault currents.

Earth electrodes may be exposed to three conditions, which have been called long-duration loading, short-time overloads, and long-time overloads. These are defined as follows:—

(i) Long-duration loading is loading in which the current is such that a gradual rise of temperature of the whole soil in the neighbourhood of the electrode takes place and eventually a steady temperature is attained. Such loading in the case of a clay soil is accompanied by a fall of resistance and no appreciable drying of the soil.

(ii) Short-time overloads are overloads in which drying of the soil adjacent to the electrode takes place in a short time, and in the consideration of which conduction of heat away from the neighbourhood of the electrode may be neglected.

(iii) Long-time overloads are overloads in which the rate of heating is in excess of that for long-duration loading, and less than that for short-time overloads; the temperature gradient away from the surface of the electrode is steeper than with long-duration loading, and heat conduction to the surrounding soil from the surface of the electrode cannot be neglected.

Each type of loading may be associated with either direct or alternating current, and with Class (i) in particular there is a marked difference between the two.

(a) Long-Duration Loading with Alternating Current

To investigate this problem, current was passed between each of the following pairs of electrodes, which were installed in weathered London clay:—

Two copper spheres, one 6 in. dia. and the other 12 in. dia.

Two 6 ft. × $1\frac{1}{4}$ in. dia. galvanized M.S. tubes, one being treated with 1 cwt. of salt.

Two 3 ft. square × $\frac{1}{8}$ in. thick M.S. plates buried vertically with the top edge 3 ft. down, one being surrounded with a coke-breeze bed measuring 4 ft. 6 in. square × 1 ft. 6 in. thick.

Current was allowed to flow until steady temperatures were attained, which usually took place in about four weeks, though when exceptional changes of weather conditions occurred from two to three months were required. During this period measurements were made of the electrode resistance and temperature, and the temperature and resistivity of the surrounding soil at various distances from the electrodes. The latter measurements were effected by means of special resistivity probes working on the four-electrode method and, in addition, containing thermocouples for determining the soil temperature.

The results for the 6-in. dia. sphere are shown in Fig. 12. These curves have been smoothed out, and do not show the day-to-day variations. Certain irregularities occur in the results which are attributed to external causes, but on the whole the results have not been seriously influenced in this way. This is probably due to the impervious nature of the clay; similar success might not be achieved in sandy soil.

The 6-ft. pipe in soil and the 3-ft. square plate behaved similarly to the 6-in. sphere after being on test for rather over a year. The change of resistance of all the electrodes is shown in Fig. 13. In all cases the resistance fell very considerably as the current was increased, owing to the negative temperature coefficient of the soil, until one electrode of each pair attained a surface temperature of about 100° C., when a very large increase of resistance took place. It is interesting to note that in the case of the 6-in. spheres, temperature variations were noted up to 4 ft. away, and at 8 ft. away in the case of the 12-in. sphere.

As the result of plotting and examining 3 500 soil-resistivity measurements made on the 50 probes surrounding the electrodes, the following conclusions have been reached:—

(i) The resistance of the electrodes varied in the same manner as the resistivity measured by the probes, though individual variations of resistivity were greater than the resistance variations.

(ii) In several cases values of resistivity of less than 100 ohm-cm. were recorded, and, in a few, values of less than 50 ohm-cm. The lowest values occurred at the highest temperature.

(iii) The increase of resistance of an electrode when it is approaching a condition of instability is mainly a surface effect. This was proved by the fact that in this condition only very slight change was shown by the nearest probes to the electrodes, and none at all by the more distant ones.

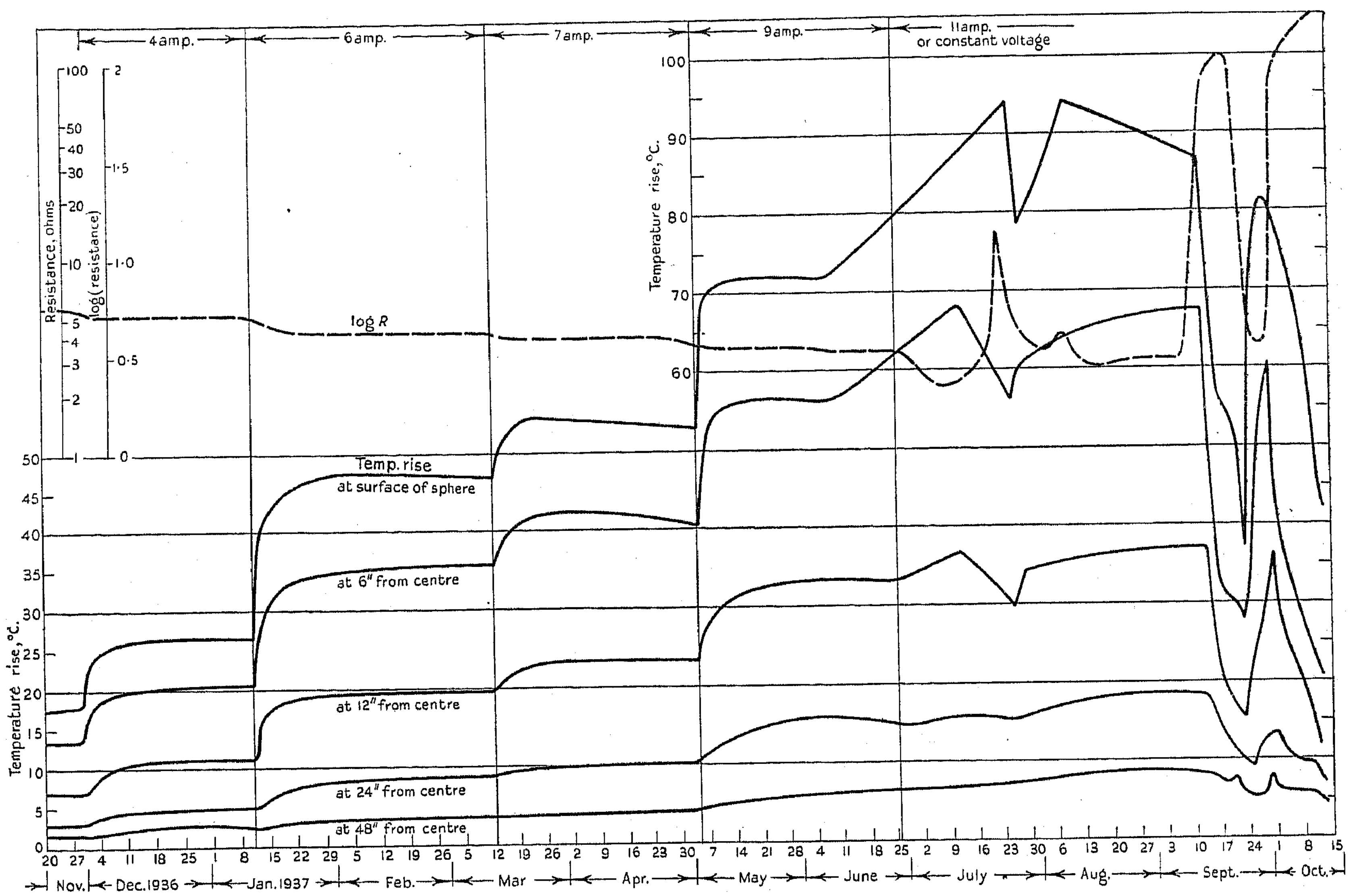

Fig. 12.—Temperature-rise and resistance curves for a 6-in. sphere.

A detailed analysis of the results, with a comparison with the theory developed previously, will be published later, both for these long-duration tests and for the other tests described below.* It is useful to record here, however, that the temperature measurements made on the surface of an electrode during a period when an abnormal increase of resistance occurs shows that it is at, or in the neighbourhood of, 100° C. This is illustrated in Fig. 14, from which it will be seen that falling-off of the current following a temperature of 100° C. is followed by a fall of temperature, and consequently a drop of resistance and increase of current. This in turn leads to a fresh rise of temperature, and the procedure continues in a periodic manner.

Whether an electrode exposed to long-duration loading will ultimately attain a temperature of 100° C. or not depends on the voltage drop across it; if this exceeds about 30 volts in clay soil of the type investigated at Alperton the electrode—irrespective of its size or shape—will eventually fail. It is unlikely that a much lower value than this would apply to any normal soil, and in some cases the value is appreciably higher. Research is to be extended to include other types of soil.

(b) Long-Duration Loading with Direct Current

Owing to the generation of gas at the surface of two electrodes in an electrolyte between which a direct

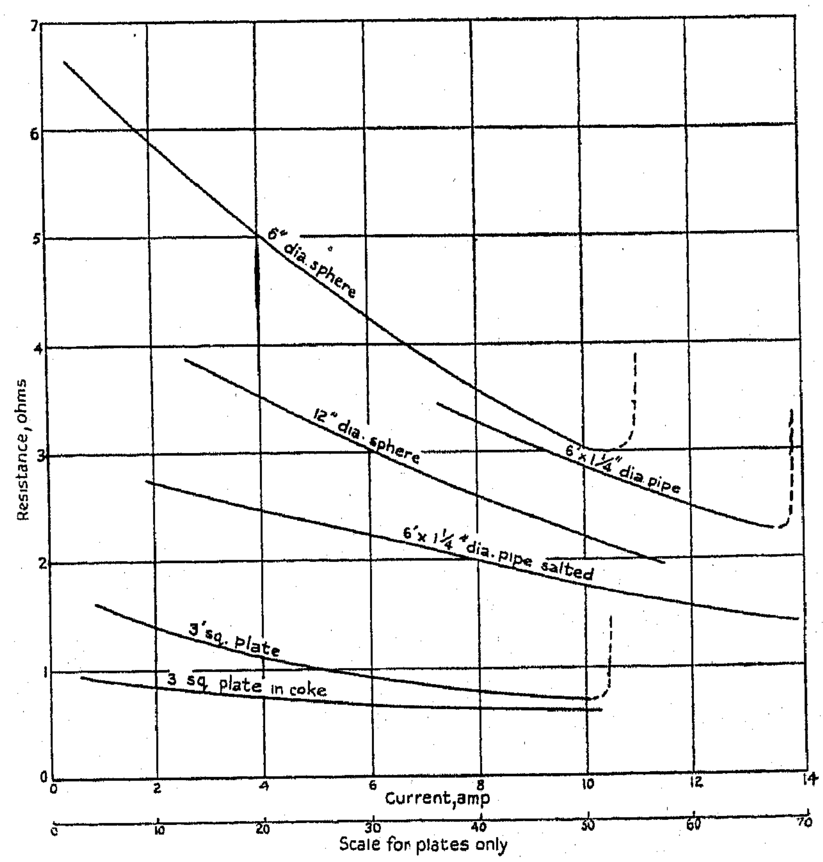

Fig. 13.—Change of resistance of electrodes with current: tests in clay soil.

* Full details are given in E.R.A. Report Ref. F/T135, "Current Loading Tests on Earth Electrodes in Clay Soil," by H. G. Taylor.

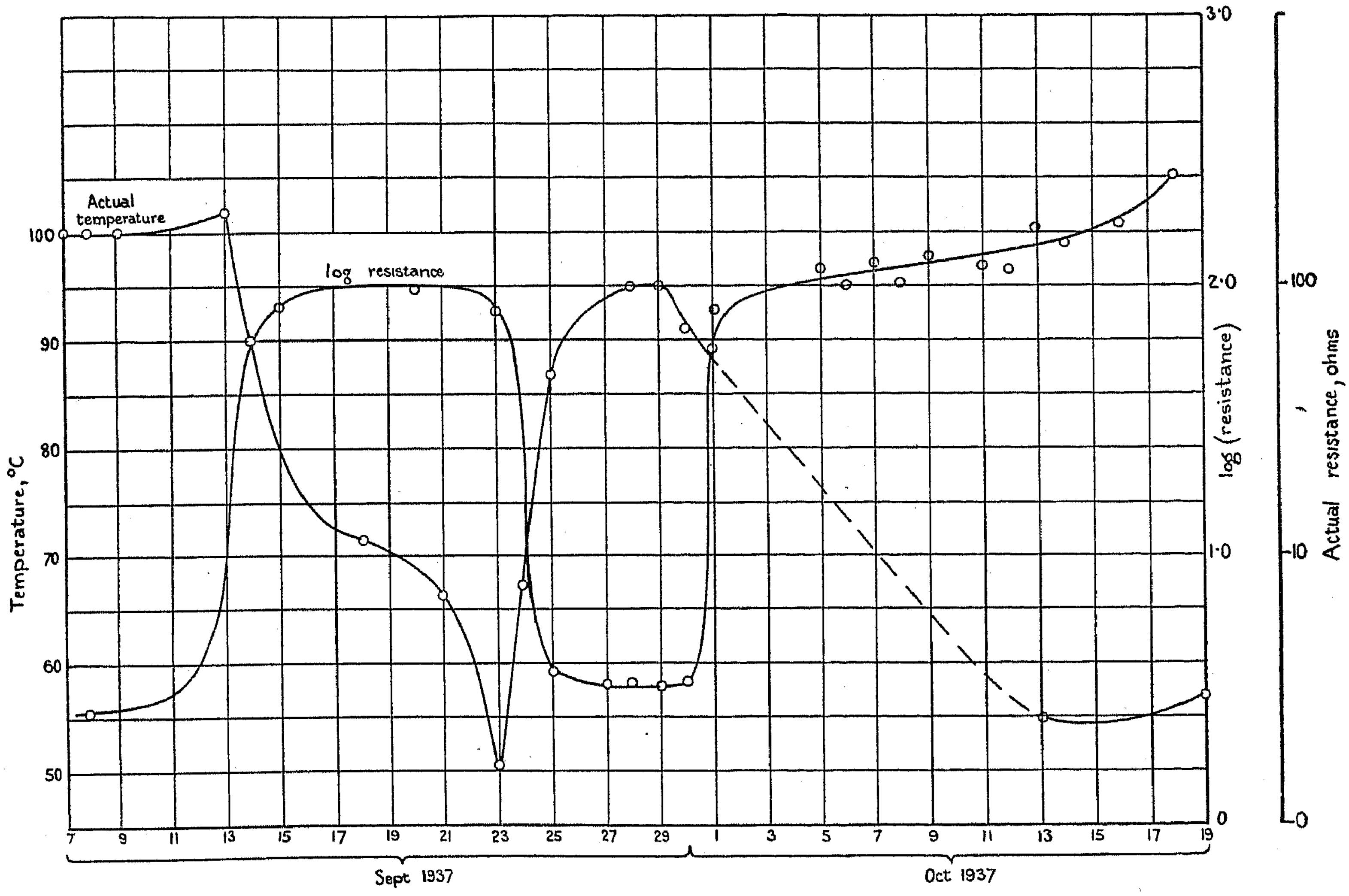

Fig. 14.—Resistance and actual-temperature curves for 6-in. sphere at the critical point.

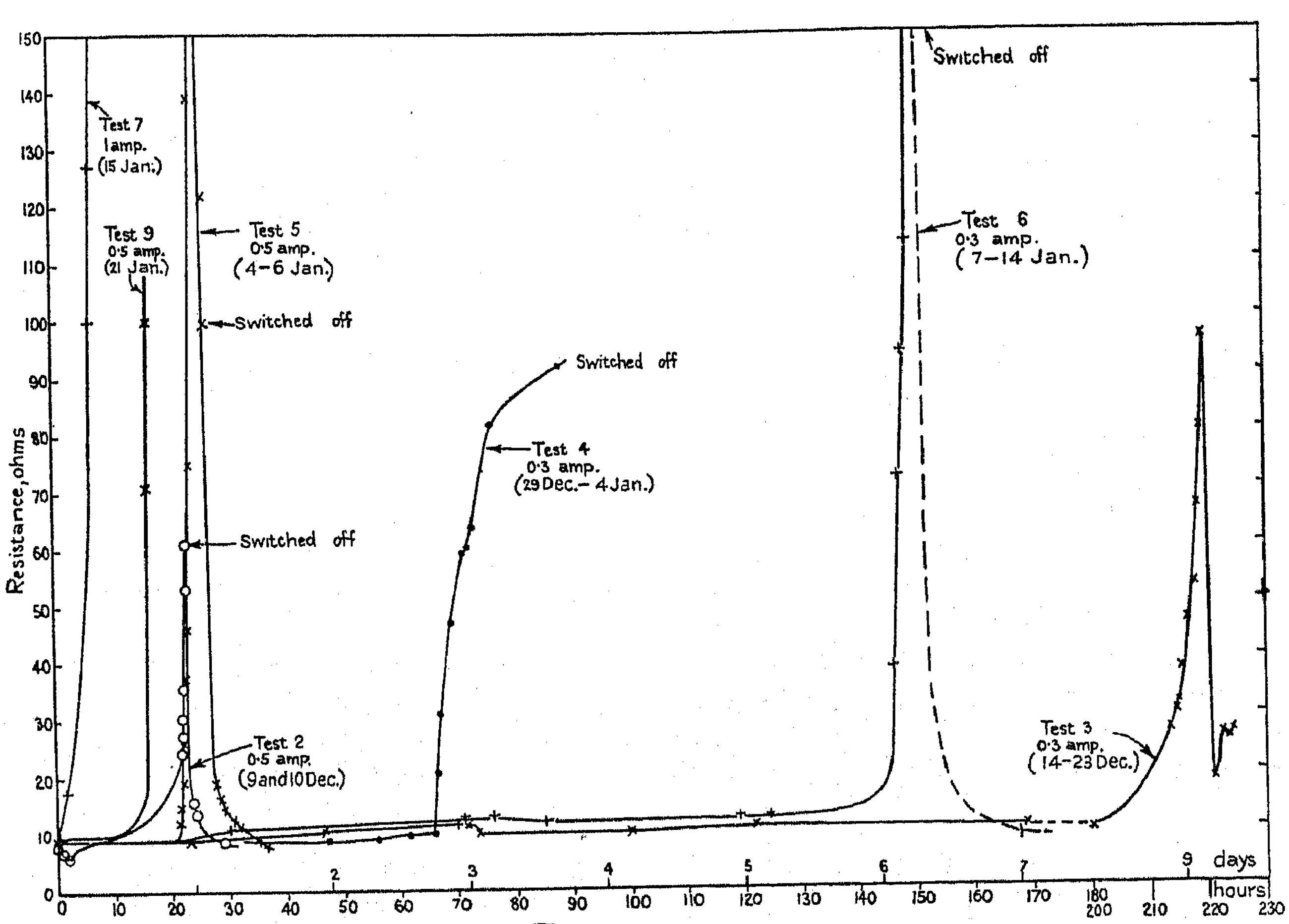

Fig. 15.—Change of resistance of 6-in. dia. spherical electrode with time. (Direct current tests—electrode connected to positive main.)

current is flowing, and also on account of the movement of moisture in the direction of the current, i.e. towards the negative electrode or cathode, changes take place in the resistance of earth electrodes on a d.c. system which are appreciably different from those occurring on an a.c. system. With alternating current about 10 amperes can be carried indefinitely by two 6-in. dia. spheres, but a direct current of 2 amperes increased the resistance of the same electrodes to a high value in a few hours; 0·5 ampere was therefore chosen for the second test, with the result shown in Fig. 15, which also depicts the results of subsequent tests.

The conclusions reached from these investigations are:—

(i) That very small direct currents (less than 0·5 ampere) could not be carried indefinitely by 6-in. sphere electrodes in clay soil without such an increase of resistance of the positive electrode as to render it useless for protective purposes—the positive electrode being understood to be that one by which current enters the soil.

(ii) That the change of resistance of a negative electrode was negligible in comparison with that of a similar positive one.

(iii) That the behaviour of the electrodes was erratic and probably materially affected by the state of the ground and the amount of rainfall.

(iv) That on the removal of the applied voltage the normal resistance was recovered in a short time (not more than an hour, and in some cases a few minutes).

(v) That in some cases recovery of a normal resistance took place (at least temporarily) without the removal of the applied voltage.

(c) Overload Capacity with Alternating Current

(i) Short-duration overloads.

The first tests on short-duration overloads were made in a 16-in. dia. hemispherical metal bowl, current being passed between copper spherical electrodes and the bowl.

On applying the voltage it was found that a comparatively steady current flowed for a short while, but the resistance then suddenly increased to a high value and the current fell almost to zero. During this period the temperature at first rose at a uniform rate and subsequently at a somewhat lower rate until a maximum was reached a short time after the increase of resistance. On removal of the electrode from the sifted loam in which the tests were made, a layer of dry soil about $\frac{1}{8}$ in. thick was found to surround it. A typical oscillogram is shown in Fig. 16.

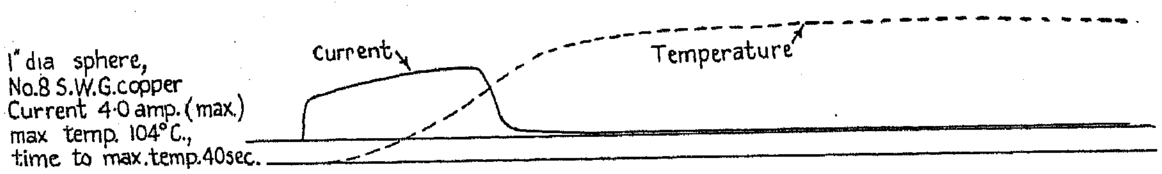

Fig. 16.—Oscillogram of a short-time overload applied to a copper sphere in loam.

In a previous paper* it was deduced from theoretical considerations that the behaviour of two electrodes under short-time overload could only be compared on a basis of the specific loading, which is equal to $i^2\rho$, where i is the current density at the surface of the electrode and ρ the resistivity of the soil. If the soils vary, the expression $i^2\rho/(\sigma\delta)$ should be used in place of $i^2\rho$, where δ is the density and σ the specific heat. The time to reach a given temperature is inversely proportional to the specific loading, and thus when the specific loadings are equal the times for the soil at the surface to attain a temperature of 100° C. are equal, and the large increase of resistance which renders the electrodes useless for protective purposes occurs in the same time. The lower the value of the specific loading the longer the "life" of the electrode.

The adoption of specific loading as a criterion of life led to a number of conclusions respecting the effect of size, resistivity, and voltage on the life of an electrode, and all these have been confirmed by tests on various model electrodes, thus justifying the adoption of this criterion. The model tests were also found to agree well with tests on an actual electrode in a different type of soil.

The experiments which have been made lead to the conclusions that abnormal increase of resistance of an electrode occurs when a given volume of steam is generated per unit area of the electrode, and that factors such as the heat capacity of the soil and of the electrode may be ignored by comparison with the heat required to vaporize the water. For clay and loam soil, constants were obtained which have enabled a simple formula to be given for determining approximately the life of any electrode subjected to a short-time overload. It is as follows:—

$$t = \frac{2\,400}{s} \text{ seconds}$$

where t = life, in sec.
s = specific loading = $i^2\rho$
i = current density on the electrode surface, in amp./sq. in.
and ρ = soil resistivity, in ohm-cm.

This formula is most accurate when the time is short (say, less than 10 sec.) and under-estimates the life of the electrode as the time increases, owing to the loss of heat by conduction away from the surface. When an extended electrode such as a strip is used or when several electrodes are connected in parallel, the life may be affected by non-uniformity of current distribution.

(ii) Long-duration overloads.

To determine the overload capacity over a long period, currents approaching 100 amperes were passed between a 6-in. copper sphere and another very large electrode which could be relied upon not to change its character-

* E.R.A. Report Ref. F/T81; and *Journal I.E.E.*, 1935, 77, p. 542.

istics during the tests. Fig. 17 illustrates the type of result obtained. With increasing temperature the resistance fell and the kilowatts increased until the temperature became too high, when a large increase of resistance occurred at the same time as a drop in energy dissipation to a small value. In some cases when the voltage was maintained the behaviour of the electrode proved to be periodic, and a particularly good example of this is shown in Fig. 18, which is an autographic current record taken over a period of 2½ days. The maximum value of the current peaks is between 30 and 40 amperes, and the current flowed for a period varying from 1 hour (for the first peak) to 5 minutes. The average value was about 10 minutes, and the average interval between peaks about 1½ hours.

The explanation of this phenomenon is that at the time of the test the soil in the vicinity of the electrode was waterlogged. On the application of voltage a heavy current flowed which very soon resulted in the generation of such a volume of steam that the resistance increased and the current fell to a negligible value. Cooling then took place, and condensation of the steam at the outside of the layer; the water gradually returned, and eventually, when complete condensation had taken place, re-made contact with the copper sphere. The current then rose once more to a high value, and the cycle was repeated. Non-uniform current density may account for the generation of more steam than is actually required to cause a large increase of resistance, and may explain the low frequency of the phenomenon.

A number of tests of a similar nature to those described above were made on two pipe electrodes, and in addition the temperature of the electrode itself was measured. It was found that the latter rose to well over 100° C., and a maximum value of 142° C. was obtained. Tests were made on the unsalted electrode at 120, 200 and 400 volts, and on the salted electrode at 120 and 200 volts. In the case of the latter electrode the current was over 100 amperes at 200 volts, and with the apparatus available it was not possible to make tests at a higher voltage.

A comparison of results shows that the loading capacity of the salted electrode is appreciably higher than that of the unsalted one, though the difference is not as great as was shown in tests made by Creighton.* The kilowatt-hour capacities were as shown in Table 6.

Table 6

Voltage of test	Salted pipe	Unsalted pipe
volts	kWh	kWh
120	17·8	13·9
200	5·6	3·8
200	6·6†	—
400	—	6·6

† Test switched off after half an hour (while resistance was still decreasing) owing to excessive current.

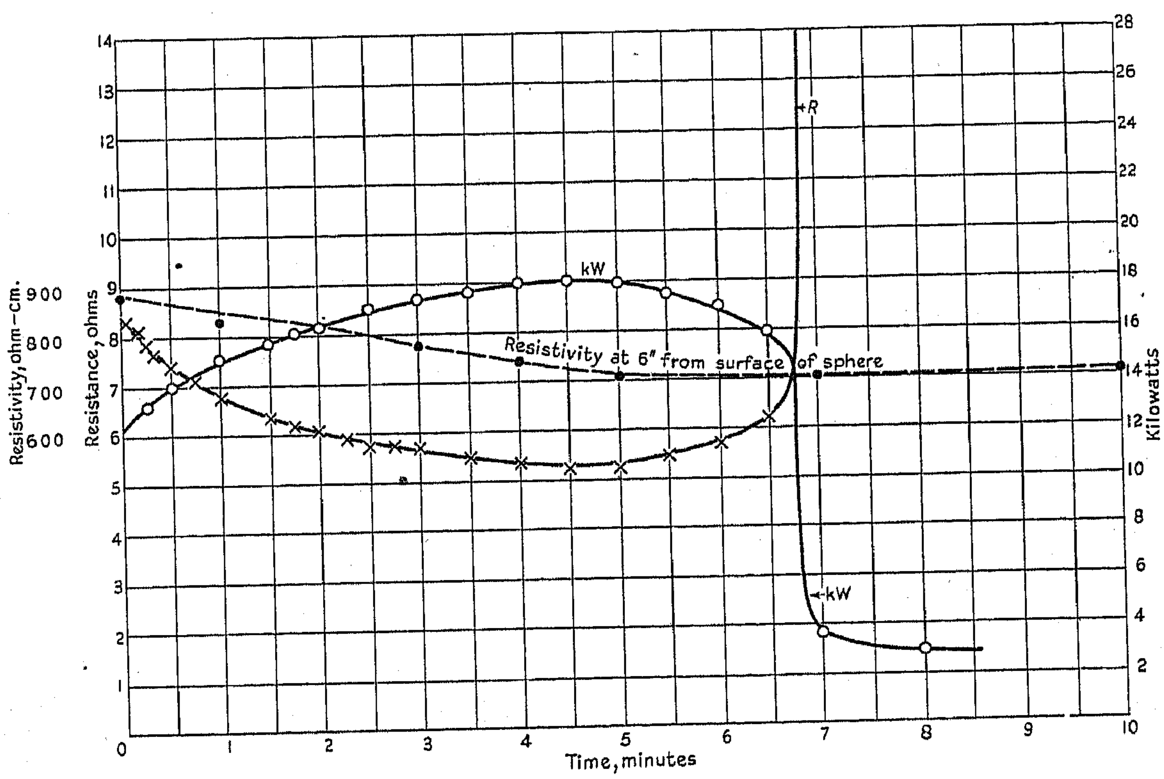

Fig. 17.—Alternating-current overload test on 6-in. dia. spherical electrode at 360 volts.

(d) Overload Capacity with Direct Current

No short-duration overload tests have been made with direct current, but the results of a series of long-duration tests are shown in Fig. 19. Six-inch diameter copper spheres were used for the test, and in each case the tested electrode was positive. The periodic feature shown in test No. 16 also occurred in test No. 19, and continued with diminishing intensity every few hours for the next 2½ days. At this time the interval between peaks had lengthened to 12 hours. The record is appreciably different from the one obtained on alternating current (Fig. 18), probably owing to polarization and other effects present with direct current and absent with alternating current. The investigations showed that

* *Journal I.E.E.*, 1935, **77**, p. 557.

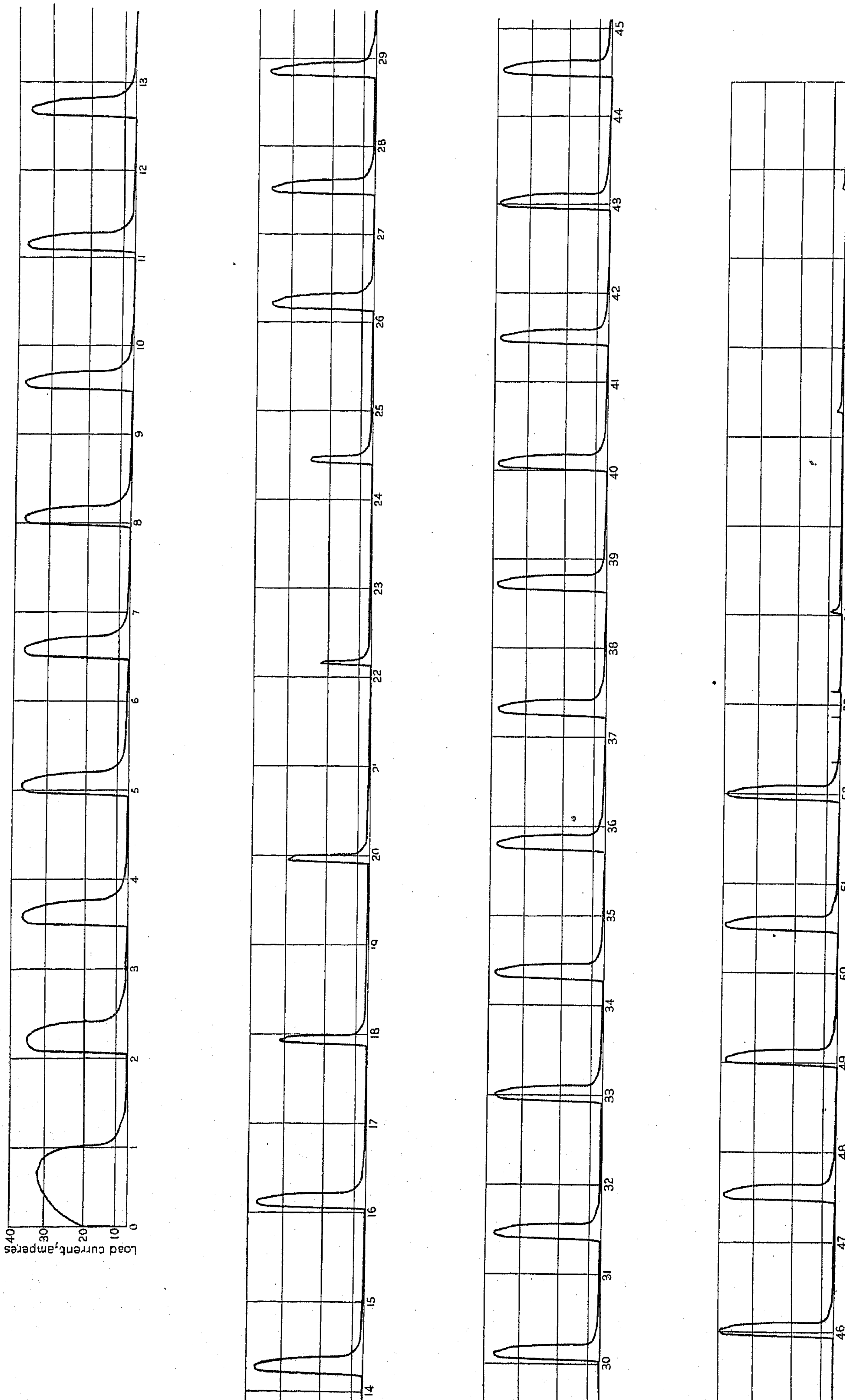

Fig. 18.—Alternating-current overload test on 6-in. dia. spherical electrode at 150 volts (autographic current record).

with long-duration overloads the capacity of electrodes on direct current is not appreciably different from that on alternating current; on ordinary loading there is, however, very considerable difference, as is shown in Sections (6) (*a*) and (6) (*b*).

(e) Conclusions

The following are the conclusions of practical importance which have been reached as a result of the research on current-loading capacity. The work is incomplete, as it has been restricted to clay and loam soil, but tests on entirely different soils are planned and other features of importance are being investigated.

(i) Failure of all electrodes in clay and loam soil is caused by the attainment of a temperature of approximately 100° C. at the electrode surface. At this temperature the moisture present evaporates and the resistivity of the soil increases to a very high value.

(ii) The time-to-failure depends on the type of loading—whether long-duration loading, short-time or long-time overloading—and may be determined from a knowledge of the characteristics of the electrodes and the soil.

(iii) In clay soil, with alternating current, small leakage currents flowing for a long time do not impair the characteristics of an electrode, since they reduce its resistance.

(iv) Small direct currents seriously impair an electrode's characteristics if they flow for a sufficient length of time and if the electrode is connected to a positive lead. This means that in a d.c. system a fault on a main which is positive with respect to earth tends to isolate itself by increase of the consumers' earth-electrode resistance, whereas a fault or a general low insulation resistance on a main which is negative to earth is injurious to the substation electrode. This suggests that osmosis is not the only reason why earth faults are more often found on the negative than the positive conductor. The resistance at the positive electrode very quickly falls after the supply has been switched off, and a test with an alternating current may not reveal any abnormal increase.

(v) The overload capacity of a salted electrode is higher than that of an unsalted one.

(vi) The overload capacity of a coke-treated electrode is very much higher than that of an untreated one if the amount of coke used is sufficient considerably to increase the surface in contact with the soil.

(vii) Heating of the soil around an electrode has the advantage that the moisture present absorbs an increased amount of salt from the soil, and on the fall of temperature this salt may remain in solution, and thus the electrode resistance may be permanently reduced.

(viii) The overload capacity of an electrode is roughly the same with direct current as with alternating current.

(ix) Until the temperature at the surface of an electrode approximates to 100° C., the voltage gradient on the surface of the ground does not alter sufficiently to affect appreciably the shock risk to animals.

(x) The life of an electrode exposed to short-time overload is inversely proportional to the specific loading, which is given by $i^2\rho$, where i is the current density on the electrode surface and ρ the resistivity of the soil.

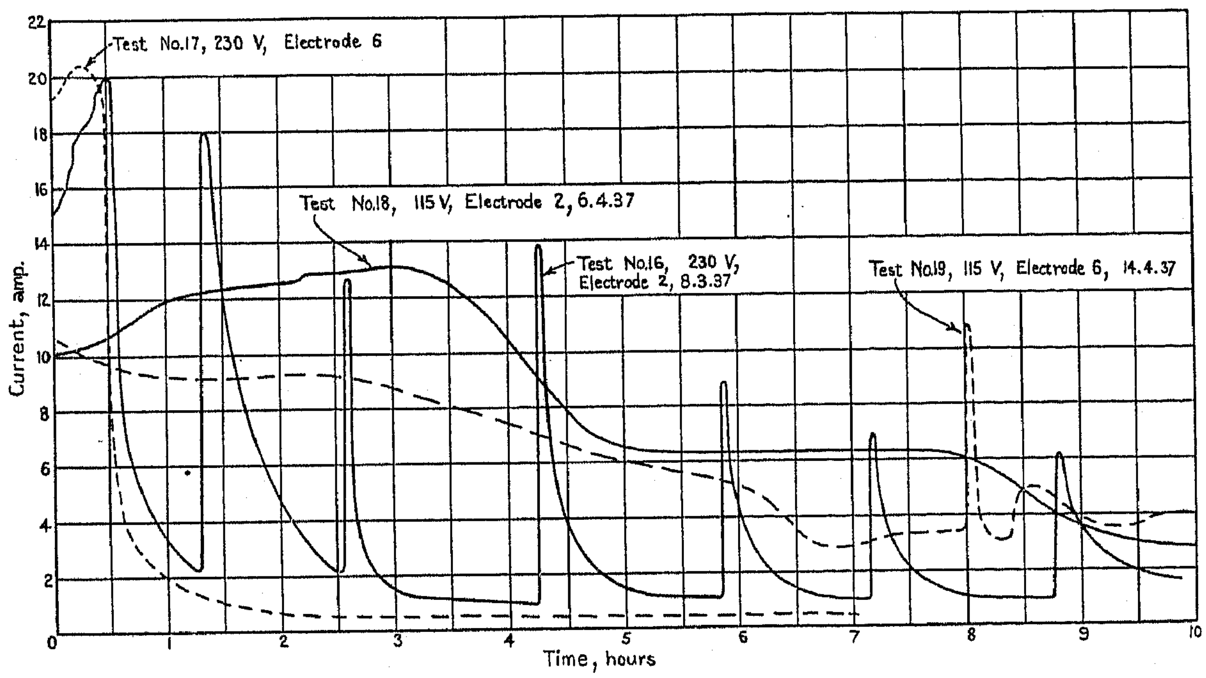

Fig. 19.—Direct-current overload tests on 6-in. dia. spherical electrodes.

(7) DESIGN OF AN EARTH-ELECTRODE INSTALLATION

(a) General Considerations

To be satisfactory, an earth electrode must comply with the following requirements:—

(i) It must have a sufficiently low resistance, at any time of the year, to pass enough current to operate the protective gear under fault conditions.

(ii) It must carry the fault current for a sufficient time to operate the protective gear without excessive increase of resistance, i.e. it must have adequate current-carrying capacity.

(iii) The voltage gradient on the surface of the ground around the electrode must not be dangerously steep.

Table 7

USES OF EARTHING

S = strip or conductor. R = driven rod or tube. P = plate or buried pipes. C = coke trench or bed. F = framework of building. CS = cable sheath. W = water main.

Classification	Purpose of electrode	Regulations	Recommended type of electrode	Points to be considered: Technical: Item	Technical: E.R.A. reports	Technical: Other bibliographical references	Economic	Remarks
H.V.	Neutral point (direct)	E.S.R., 1937–38	R, S, P, C, or CS	(a) Resistance should be low enough to permit protective gear to operate. (b) The life of the electrode under short-duration fault conditions should be greater than the time required to operate the protective gear at any fault current.	Ref. F/T50, 71, 81, 86, 102, 114, 118, 135	"Copper for Earthing"*	In certain cases where the loading is very high, plates may prove the cheaper proposition, despite the cost of excavation. For equal resistance, driven rods or strips are much cheaper than plates. With rods the cost of special means for driving long coupled rods should be compared with the extra cost of connections and space required for connecting a number of short rods in parallel. Rods are more easily salted than strips. Extra cost of coke treatment of plates should be weighed against advantages.	
	Neutral point with Petersen coil	—	R, S, P, or C	(c) The current rating of the electrode should exceed that of the Petersen coil. This may be quite high to permit operation for several hours with one phase earthed. (d) The resistance should be as low as possible—precise details are not available, but a value of not more than 5 ohms is tentatively suggested.	—	H. W. Taylor and P. F. Stritzl† Paris H.T. Conference, 1939, Papers 309 & 319	—	
	Steel-tower lines and earth wire	Overhead Line Regulations of the Electricity Commissioners, El.C. 53, Revised—14 E.S.R., 1937—14 (b), 30 (b) (iii)	R or S	(e) Each tower should have such an earth resistance that flashover from tower to lines cannot occur with maximum possible lightning current. (f) In clay soil, footings alone will often provide a sufficiently low resistance. In very high-resistivity soil a counterpoise may be necessary.	Ref. F/T127	Ref. F/T113 contains a bibliography.	It is uneconomic to provide electrodes for all towers irrespective of footing resistances; these should be measured first.	
	Metalwork on wood-pole lines and other metalwork	Overhead Line Regulations of the Electricity Commissioners, El.C. 53, Revised—14 E.S.R., 1937—14 (b), 30 (b) (iii)	R, S, or P	(g) Metalwork to be earthed at each pole or four times per mile if earth wire is used. In former case it is difficult to obtain sufficiently low resistance to blow fuse, and in such a case voltage gradient at base of pole will frequently be dangerous.	—	—	Compare cost of earth wire with cost of satisfactory earth electrode at each pole.	
	Electrode boilers	E.S.R., 1937—8 (v) I.E.E., 1939—711	CS	—	—	—		
L.V. and medium voltage	Neutral point (ordinary earthing)	E.S.R., 1937—4 I.C.E., 1938 I.E.E., 1939	CS, W, R, S, or C	(h) Resistance should be low enough to enable distribution system faults to be cleared, and not to affect appreciably blowing of consumers' fuses on earth faults. (j) Electrode should be situated where cattle have no access, or voltage-gradient dangers should be avoided by suitable design of electrode.	Ref. F/T50, 69, 81, 102, 104, 114, 118, 122, 135	"Copper for Earthing"*	It is often cheaper to provide an earth electrode in a safe place rather than to provide a special electrode free of dangerous voltage-gradients.	
	Neutral-point and distributor earths when using protective multiple earthing	Electricity Commissioners' Special Regulations	R or S	(k) Total earth resistance of each distributor or group of distributors should not exceed 2 ohms; 10-ohm earth to be installed at end of each distributor, and 4-ohm earth at substation if only one group of distributors fed by a single line.	Ref. F/T102, 122	—	Cost of these earths in areas of very high resistivity justifies the consideration of neutralization as an alternative.	Short lengths of cable sheath or water pipes should be used if they exist.

* A Copper Development Association publication.

† H. W. TAYLOR and P. F. STRITZL: "Line Protection by Petersen Coils," *Journal I.E.E.*, 1938, 82, p. 387.

Table 7—continued

L.V. and medium voltage	D.C. system neutral point	E.S.R., 1937—4 (v) I.E.E., 1939 I.C.E., 1938	R, S, or P	(*l*) Area of electrode should be so large that a fault on the negative main does not cause a very high electrode resistance due to the generation of gas on its surface. (*h*) above also applies here.	Ref.F/T50, 135	—	—	
	Tramway system earth	Ministry of Transport "Regulations for Earthed Traction Systems"	R, S, P, or W	(*m*) Two separate electrodes are required situated not less than 20 yd. apart, resistance not more than 2 ohms when connected in *series*. Possible cheaper alternative—water main not less than 3 in. int. dia.	—	—	—	
	Consumers' apparatus (ordinary earthing)	I.E.E., 1939 E.S.R., 1937—29 (*a*) (i) I.C.E., 1938 H.O. Elect. Regs. 13 and 21	CS, W, or P	(*n*) For complete protection, resistance should be so low that when combined with all the other resistances in the circuit twice the operating current of the largest fuse in the installation will flow at the maximum safe voltage. The I.E.E. Regulations only require that this current shall flow at mains voltage.	Ref.F/T50, 69, 81, 82, 102, 104, 114, 118, 122, 135	"Copper for Earthing"* *Elect. Power Eng.*, 1938, **30**, p. 777	Except for lighting consumers, it is expensive in high-resistivity areas to provide a satisfactory earth other than by connection to water mains or cable sheath.	Occasionally houses are grouped and strips or conductors used for earthing.
	Consumers' apparatus (protective multiple earthing)	Electricity Commissioners' Special Regulations	R	(*o*) Any water pipes or other existing low-resistance earth electrodes to be used; otherwise a 6-ft. rod or pipe must be driven as nearly vertically as possible.	Ref. F/T102, 122	—	A twin or concentric service avoids the cost of earth electrodes on consumers' premises. Electrodes should be no larger than is necessary for driving. Mechanical driving saves time.	
	Consumers' apparatus (earth-leakage circuit-breakers)	I.E.E., 1939 E.S.R., 1937—29 (*a*) (i) I.C.E., 1938 H.O. Elect. Regs. 13 and 21	R	(*p*) The minimum requirements are one driven electrode having a resistance of not more than 500 ohms.	Ref. F/T102, 122	"Copper for Earthing"*	½-in. dia. × 6-ft. long rods will be satisfactory in most soils.	
	Radio receiving set	I.E.E., 1939	R	(*q*) A driven rod or pipe required as near the set as possible; the resistance of the electrode should be sufficiently low to blow the fuse protecting the set.	—	*Wireless World*, 1939, **44**, p. 394	—	
	Protective earth for repairs	—	CS, W, F, or R	(*r*) A substantial low-resistance earth should be used whenever possible; such connections are usually temporary.	—	—	—	
	Electrode boilers	E.S.R., 1937—4 (viii) I.E.E., 1939—711	CS	—	—	—	—	
Miscellaneous	Lightning arrester	—	R or S	—	Ref. F/T50	—	—	
	Lightning conductor	—	R or S	(*s*) A resistance of less than 5 ohms is desirable and durability should be considered of primary importance; contact of dissimilar metals should be avoided. Coke should not be used with copper.	—	—	Low resistance and durability are the essential features, and these may be obtained more cheaply with plain copper rod than with more complicated devices.	
	Static	—	R or F	(*t*) Electrode resistance is unimportant; earthing lead need only be large enough to avoid mechanical damage.	—	"Copper for Earthing"*	—	

Regulations.—I.E.E. = Institution of Electrical Engineers Regulations for the Electrical Equipment of Buildings.
I.C.E. = Institution of Civil Engineers Regulations for Earthing Electrical Installations to Metal Water Pipes and Water Mains.
E.S.R. = Electricity Supply Regulations of the Electricity Commissioners.
H.O. = Home Office—Factories Act, 1937, Electricity Regulations.

* A Copper Development Association publication.

(iv) The electrode and its connection must have a high resistance to soil and atmospheric corrosion.

(v) For certain cases the electrode must have a sufficiently low surge impedance to prevent a flashover from earthed metalwork to insulated conductors when a lightning discharge takes place.

Until recent years no serious attempt had been made in this country to design earth electrodes. The situation is now changing, and attention is being very widely given to item (i) above. Some consideration is being given to items (iii) and (iv), but beyond this electrodes are not designed. This is to a large extent due to the absence of reliable data on which to base designs, but is also due to some extent to a lack of appreciation of the conditions which electrodes have to meet. Conditions in this country have not until recent years made it necessary to give consideration to item (v).

In low-voltage installations, items (i), (ii), (iii) and (iv) must be considered, and in high-voltage installations (i), (ii), (iv) and (v).* It is advantageous to consider the two types separately.

Table 7 shows a list of all general uses of earth electrodes arranged in three classes—viz. electrodes for high-voltage systems, electrodes for low- and medium-voltage systems, and electrodes for miscellaneous uses. The regulations covering the various uses are shown in the third column, and in the fourth the type of electrode which is recommended is indicated. In this connection it should be realized that there are several matters which should be considered irrespective of the use of the electrode; these are as follows:—

(i) For what length of time is the electrode expected to remain in a satisfactory and reliable condition? If the required life is long, and if inspection or testing are not expected to be carried out, then additional money must be spent to secure a durable electrode.

(ii) Is the soil at the site of uniform resistivity, or does the resistivity increase or decrease with depth? If the fomer is the case, shallow electrodes are preferable; if the latter applies, the deeper the electrode the better. Useful information on the stratification of the soil may be obtained from geological drift maps or from inspection of nearby quarries, cuttings or excavations.

(iii) Is the artificial treatment of the electrode either with coke or with salt justified? E.R.A. Report Ref. F/T118 contains details of coke treatment of electrodes.

(iv) Is a bed of clinkers required for drainage on the site? If so, coke breeze may be substituted and used to provide a low-resistance and durable electrode (E.R.A. Report Ref. F/T114).

(v) In soil of high resistivity would any other method of protection be cheaper and more satisfactory than ordinary earthing? Alternative methods of protection on l.v. systems are described in E.R.A. Reports Refs. F/T102 and F/T122.

(vi) If the soil resistivity at the site is high, can the earthing be effected at some other more suitable place? A special earth wire may be run to the preferable site, or the neutral wire may be earthed there instead of at the substation.

* Item (iii) is not unimportant, but it is impracticable to ensure a safe voltage-gradient on high-voltage systems merely by design or disposition of the earth electrode.

(vii) How much is it possible to spend on earthing and other protective means as an insurance against accidents through electric shock? In this connection it should be remembered that the total cost is a function of the number of consumers plus a fixed charge, and consequently the smaller the area supplied the larger the cost per consumer and the smaller the profit on the scheme for a given degree of protection.

(viii) In all earth-electrode installations particular care should be taken to ensure that the electrode is installed and connected up in a permanent and efficient manner, since once it is installed it is the most likely part of the whole system to be completely ignored for years. The I.E.E. Regulations for the Electrical Equipment of Buildings state that "Every connection of an earthing lead to a pipe, conduit, cable-sheath, armouring, or earth electrode, shall consist of a substantial clamp, constructed of a non-rusting material such as copper, and the contact surfaces shall be clean." According to soil-corrosion studies of the Bureau of Standards extended over a period of eight to twelve years, the average rate of corrosion of wrought iron and mild steel in soil is 15 times that of copper. This result was obtained by taking the mean of the results for 31 different soils. There is thus an obvious advantage in using copper or copper-sheathed steel rods for earthing, and there is the further feature that by doing so contact of dissimilar metals at the connection is avoided. By using copper or a copper alloy for rod, clamp and cable, atmospheric corrosion is practically eliminated.

(b) High-Voltage Installations

The provision of a satisfactory earth for a system neutral point is a matter requiring careful consideration and a knowledge of the characteristics of the circuit to be protected, the characteristics of the protective relay, and the soil conditions at the site. Where instantaneous tripping is provided, low resistance should primarily be aimed at, and this indicates driven rods, which should not be installed at the substation in accordance with a set plan, but rather concentrated in that part found to have the lowest resistivity, as determined by measurement of the resistance of trial electrodes after installation or by using the four-electrode method. Where time-delay relays are provided, they generally have such a characteristic that whatever the fault current the time required to operate is such that the temperature rise of the protected apparatus is a constant. This means that the time is inversely proportional to the square of the current. Now the temperature rise of an earth electrode follows the same law, and therefore in designing an electrode to meet certain conditions it is only necessary to ensure that the time for the relay to operate at any given current is less than the life of the electrode at the same current. The latter may be determined for London clay from the formula previously given relating the life of the electrode to the specific loading. Investigation is now planned to determine the constant in this formula for other soils.

The design is not straightforward, since the fault current is dependent on the resistance of the earth electrode, which in turn depends on its size, and conse-

quently any change in the resistance of the electrode affects the loading capacity in two ways—by change of fault current and by change of surface area of the electrode. It is therefore essential to know the impedance of the fault-current circuit, and it will be necessary to make some assumption about the maintenance or otherwise of the supply voltage during fault conditions. Where the current is of the order of thousands of amperes, a considerable surface area is required to dissipate the energy without failure of the electrode, and this can only be provided by a generous use of driven rods on the lines adopted in the U.S.A., or by the use of plates, strips or conductors in parallel with rods.

The use of electrodes on h.v. systems other than for neutral points calls for no comments apart from those given in Table 7.

(c) Low-Voltage Installations

(i) Ordinary earthing.

There are ten main uses for earth electrodes on l.v. systems, of which the principal are those relating to neutral-point and consumer's apparatus earthing on a.c. systems using the normal method of earth-fault protection, protective multiple earthing, and earth-leakage circuit-breakers.

Whilst electricity supply was restricted to urban areas, or large villages possessing water mains, and a water supply in each house, the problem of providing adequate protection against earth faults by means of fuses did not present any serious difficulty. In recent years, however, supply has extended to rural areas where it is no longer economic to use cable (and thereby provide a metallic sheath for earthing) and where no water mains exist. Furthermore, the use of electric cookers and other large current-using appliances has considerably extended, with the result that very low earth-path resistances are required to enable the fuses to be blown. It is by no means uncommon for a 30-amp. fuse to be installed, and this may only be blown in less than a minute at the supply voltage if the earth-path resistance* is no more than about 4 ohms. To ensure complete protection, it should be possible to blow the fuse at the maximum voltage with which a person may safely make contact. Some measure of alleviation is provided by the fact that the fault usually occurs on a sub-circuit, which is probably protected with a 15-ampere fuse, thus permitting 8 ohms in the earth circuit. From this value must be deducted the resistance of the fault, the resistance of the earth-continuity conductor in the house, and the resistance of the supply mains. The net result is about 5 ohms, and this must not be exceeded by the combined earth resistance at the consumer's premises and the substation.

The cheapest method of securing such resistances is generally by means of driven rods, and Fig. 20 gives an approximate estimate of the cost of installing these. If the soil resistivity is 1 000 ohm-cm. (a value which occurs with many clays), a resistance of 0·5 ohm may be secured at the substation for a cost of about £3, and 3 ohms may be obtained at the consumer's premises for 8s. These costs are not unreasonable, but it will be seen that if the resistivity increases to 5 000 ohm-cm. the cost increases to about £8 for 1 ohm at the substation (as compared with 26s. when $\rho = 1\,000$ ohm-cm.) and £2 10s. at the consumer's premises. The latter, at least, is a value which could not be contemplated for each individual house in a village, and if the resistivity is any higher it is quite impracticable to provide protection by ordinary earthing for any but lighting consumers. A curve show-

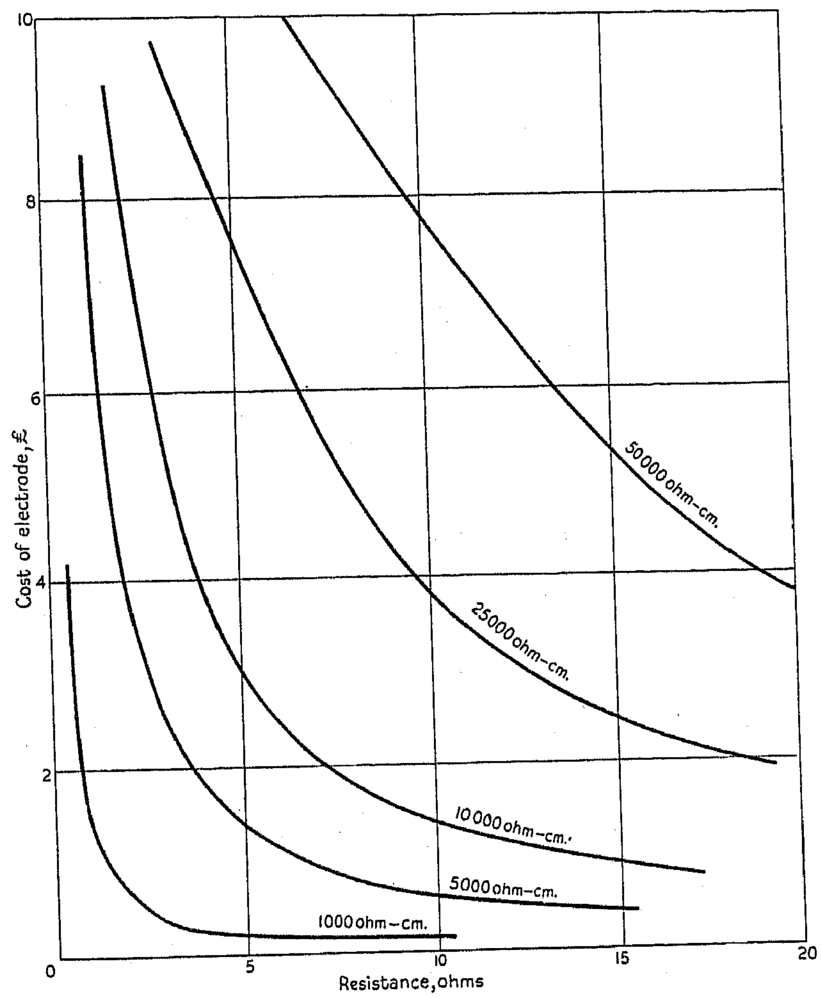

Fig. 20.—Cost of ½-in. driven copper-rod electrodes of various earth resistances.

Based on rod at 6½d. per foot and a driving charge of 1d. per foot.

ing the approximate cost of a 5-ohm strip or conductor electrode in various soils is shown in Fig. 21. It should be appreciated that cost data are only inserted here to give a general impression; local conditions may effect very appreciable modifications of such figures.

From these two sets of curves and a knowledge of the soil in the locality of the proposed distribution system it is possible to estimate the cost of providing protection by means of ordinary earthing. This may be compared with the cost of providing protective multiple earthing or earth-leakage circuit-breakers. The various items to be considered are given in the form of a Table in E.R.A. Report Ref. F/T122. Where the resistivity is exceptionally high, consideration should be given to neutralization—a form of protection in which complete reliance is placed on the neutral for clearing all earth faults.

If ordinary earthing is to be used, dangerous voltage gradients must be avoided around the electrodes and

* The earth-path resistance comprises that of the two electrodes, the line, the fault, the earth-continuity conductor, the earthing leads and the transformer winding.

adequate current-carrying capacity must be provided. The former may be ignored at the consumer's installation unless it is on a farm where cattle or horses are liable to walk near the electrode. If this is the case, then the same precautions must be taken as at a substation. The most elementary method of avoiding the risks of a dangerous gradient is to earth at some point inaccessible to cattle. The point chosen may be near the substation and an insulated conductor may be run from the l.v. neutral point, or it may be at any convenient point in the distribution system. There is no reason why the neutral point should always be earthed at the substation; equally satisfactory results are ensured by making a connection to the neutral conductor at some other point. Not only can this be made the means for overcoming the voltage-gradient trouble, but also in this way use may be made of some existing low-resistance earth electrode such as a short length of water pipe. As an alternative to choosing a safe place for earthing, electrodes may be installed at the substation site in accordance with the recommendations set out in E.R.A. Report Ref. F/T104.

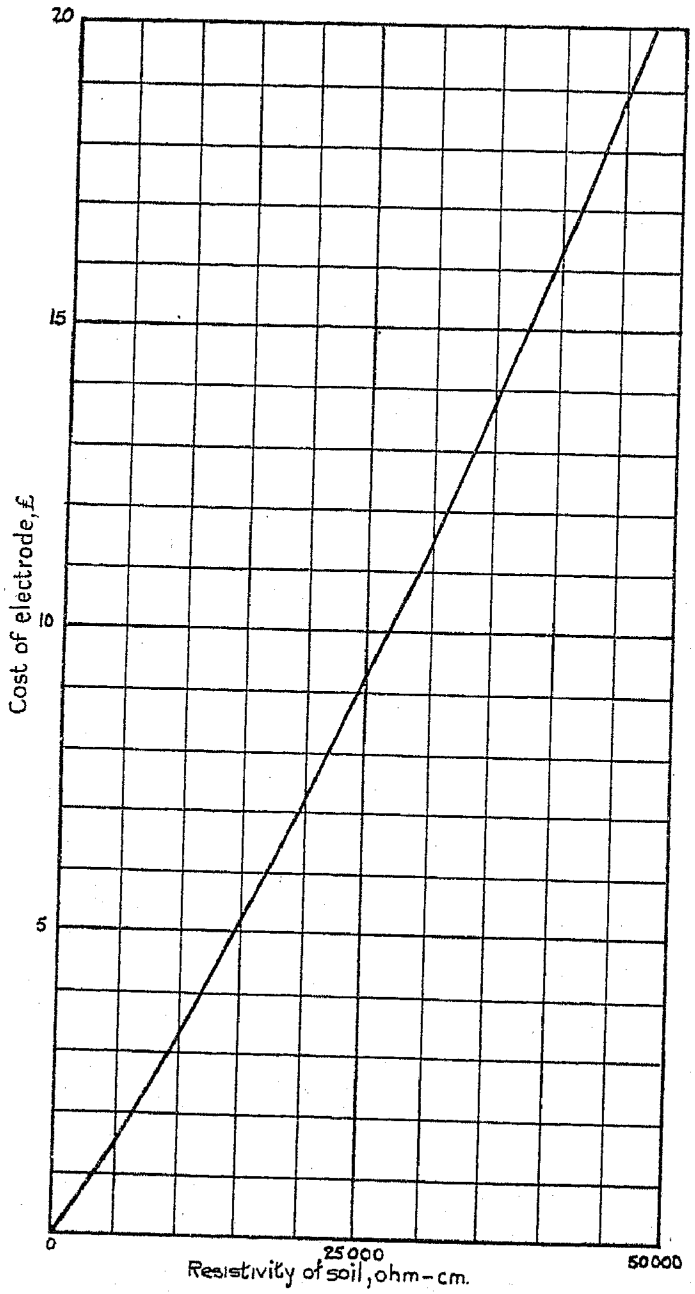

Fig. 21.—Dependence of cost of a 5-ohm earth electrode of the conductor or strip type on the resistivity of the soil.

Based on 0·05-sq. in. scrap conductor (valued at £40 per ton) and a labour charge of 1s. 3d. per yard for trenching.

The loading capacity of the substation electrode is the next most important feature. It has already been indicated how this may be determined, and with such electrodes special consideration should be given to the effect of prolonged small currents. Several resistance faults may occur on a distribution system, no one of which is of sufficient magnitude to blow any fuses, and these may flow almost indefinitely, since the majority of substations are unattended and measurements of earth currents are seldom taken. The criterion of danger is the displacement of the voltage of the neutral point with respect to earth; if this exceeds about 30 volts in low-resistivity London clay, the earth electrode will eventually fail through excessive temperature-rise. In almost any other soil the permissible value would be higher. This matter should also be borne in mind with respect to electrodes at consumers' premises; it is possible for quite appreciable fault currents to flow without the blowing of fuses, but in general there is some other indication such as shock, smell, or signs of burning. Furthermore, the electrode would be seen to be steaming before failure actually took place. It may therefore be assumed that less consideration need be given to loading capacity at consumers' premises than at substations, but it should not be ignored.

(ii) Earth-leakage circuit-breakers.

If earth-leakage circuit-breakers are employed, a 6-ft. driven rod should be used, and provided this has a resistance of not more than 500 ohms it will be satisfactory. If the resistance is greater than this, a special earth-leakage circuit-breaker must be used or the sensitivity of the protection must be sacrificed. Where such protective means are provided throughout a distribution system, the substation neutral-point earth should, strictly, have a low enough resistance to cut off the supply in the event of a live line making contact with earth. This can only be effected if the substation earth resistance is of the order of 1 ohm—a value which is difficult to secure in any but low-resistivity soil; where it is an uneconomic proposition the only safe solution is to employ an earth-leakage circuit-breaker of the substation type. Because consumers' faults are tripped at the consumers' premises there is no need to take special precautions at the substations to avoid dangerous voltage-gradients, and loading capacity can be ignored.

(iii) Protective multiple earthing.

If protective multiple earthing is used, return power current may flow continuously through both consumer and substation earth electrodes. The actual value will be relatively small, since an essential feature of this form of protection is a low-resistance neutral conductor. The permissible values for earth electrode resistance at substations and on the distribution system are laid down elsewhere.* The lower these resistances are, the safer is the system if a broken neutral wire occurs. Voltage gradient and loading capacity may largely be ignored. At consumers' premises 6-ft. electrodes are recommended.

* E.R.A. Report Ref. F/T122.

(d) Miscellaneous Uses

Electrodes for lightning arresters and overhead lines require to have a low impedance to very high frequencies. The design of such an electrode depends to some extent on the dielectric constant as well as on the resistivity of the soil, and it is not certain that in all cases the lowest-resistance electrode is the most satisfactory form. The matter is, however, being fully investigated by the E.R.A., and in the meantime it can only be recommended that the resistance of such electrodes be made sufficiently low to prevent a voltage building up in the metalwork, and causing a "backflash" to the insulated conductors with the maximum likely lightning discharge current.

(8) GENERAL CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER INVESTIGATION

Whilst complete information is not yet available on all aspects of earthing, sufficient data have been accumulated to convert earthing from a "rule-of-thumb" process based on ideas and impressions dating from the days of static electricity to a scientific process based on precise knowledge of current flow from non-geometrically shaped conductors placed in a semi-conducting medium of varying resistivity. The degree of precision with which electrodes can be produced to comply with a given specification as regards resistance is only limited by uncertainty as to the resistivity of the soil in which they are buried. Where this is uniform, the value may be determined by a simple test, and the resistance predicted with a satisfactory degree of precision; where it is non-uniform with respect to depth, only an estimate can be made. It is doubtful whether this aspect would repay much further investigation, in view of the difficulty in measuring the resistivity at various depths; a preliminary test on site with a rod electrode is the best guide.

Whilst the work which has been done on loading capacity represents a very material step forward, it cannot be regarded as final; much confirmatory and new work remains to be done. The subject is difficult, tests require considerable preparation and some long time to carry out, but it is believed that the desirable lines of investigation and methods of test have been set out with sufficient detail to ensure that future research will produce results which can be compared with those already available, and that the latter will ensure consideration being given to the question of current-loading capacity of electrodes. New work is now planned on the behaviour of different types of soil, the requirements of Petersen-coil earth electrodes, and the behaviour of long electrodes and electrodes in parallel.

The relative advantages and disadvantages of coke and salt treatment have been fairly fully investigated. The former is now completely understood; the latter requires no new tests, but the continuance of existing ones for several years. This includes the corrosion investigation, which appears to be indicating that the variation in the life of electrodes made from different materials and in different soils exceeds the variation of any material in any one soil caused by salt treatment.

Voltage gradient has at times been a serious problem, but the evidence which has been produced shows how any danger on this score may be avoided with low-voltage installations; with high-voltage installations, apart from placing the electrodes in unexposed situations, there is no relief from dangerous gradients. The only redeeming feature is that high-voltage faults are generally of very short duration compared with low-voltage faults, and also are more rare.

An inherent difficulty associated with earthing is the variability of soil resistivity. In this matter experience is the best guide, and in any one locality engineers should soon get to know what to expect from their soil. Soils have been grouped roughly according to a scale of resistivity, but special causes are always likely to produce exceptions. Such causes are purity of drainage water, prolonged dry spells, excessive salt content, unexpected strata changes, or pockets of high- or low-resistivity soil. It would be very convenient if a resistivity map could be produced on the lines of that prepared by the E.R.A. for Great Britain which shows the mean resistivity to a depth of 500 ft., but changes are so local and so subject to seasonal variation that it is very doubtful whether anything could be produced of greater value than the experience of the local engineer backed up by common sense and a few tests.

(9) ACKNOWLEDGMENTS

The authors desire to thank the Northmet Power Co. and the North-Eastern Electric Supply Co. for their co-operation throughout the 7 years during which the work has been in progress. They also wish to thank their colleagues Mr. A. H. Bennett, Mr. W. D. Tuck and Mr. W. J. Darby, for continuous interest and help, and desire to record their appreciation of the assistance they have received from many other engineers at various times. Thanks are also due to the North Wales Power Co. and the Mid-Cheshire Electric Supply Co. for the provision of facilities in connection with the tests at Eigiau and Newchurch Common respectively.

APPENDIX 1

Extract from the Electricity Supply Regulations, 1937, for Securing the Safety of the Public and Insuring a Proper and Sufficient Supply of Electrical Energy (*Reproduced by permission of H.M. Stationery Office*)

Electric Lines and Systems for Low and Medium Voltages

Connection with earth.

4. The following provisions shall apply to the connection with earth of alternating-current systems at low voltage in cases where the voltage normally exceeds 125 volts, and of systems at medium voltage employed for giving a general supply:—

(i) Unless otherwise allowed by the Electricity Commissioners, a point of every such system shall be connected with earth.

(ii) The connection with earth shall, subject as hereinafter provided, be made at one point only in each system and the insulation of the system shall be efficiently maintained at all other parts.

(iii) In the case of a system comprising electric lines having concentric conductors, the external conductor shall be the one to be connected with earth.

(iv) The connection with earth may include a switch or link by means of which the connection may be temporarily interrupted for the purpose of testing or for locating a fault.

(v) In the case of a direct-current system, an ammeter shall be permanently inserted in the connection with earth and a continuous record of the amount of the leakage current (if any) passing through the ammeter shall be taken and kept by the Undertakers. Where three-wire direct-current systems are used, a fusible cut-out or automatic circuit-breaker may be inserted in the connection with earth in parallel with a resistance of not more than 5 ohms.

(vi) In the case of an alternating-current system, there shall not be inserted in the connection with earth any impedance (other than that required solely for the operation of switchgear or instruments), fusible cut-out or automatic circuit-breaker, and the result of any test made to ascertain whether the current (if any) passing through the connection with earth is normal shall be duly recorded by the Undertakers:

Provided that for the purpose of operating relays for the remote control of switches, the Undertakers may insert in the connection with earth the secondary winding of a high-frequency transformer, the ohmic resistance of the said secondary winding not to exceed 2 000 microhms at a temperature of 60° F. and its inductance not to exceed 10 microhenrys.

(vii) Alternating-current systems which are connected with earth at one point as aforesaid may be electrically interconnected subject to the following conditions and qualifications:—

(*a*) Each connection with earth shall be bonded to the metal sheathing and metallic armouring (if any) of the electric lines concerned; and the Undertakers shall serve a notice on the Postmaster-General at least seven days prior to the making of any such interconnection, specifying the location of the point or points at which such interconnection is to be made and at which the interconnected systems are connected with earth, and the date on which such interconnection is to be made.

(*b*) Overhead lines forming a system or part of a system shall not be electrically interconnected with other electric lines (including other overhead lines) unless the neutral conductor or conductors of the overhead lines is or are of the same material and cross-sectional area as the corresponding phase conductors of the overhead lines.

(*c*) Where a system includes a generator or a transformer not having a mesh winding of low impedance, it shall not be electrically interconnected with another system if the neutral point of such generator or transformer is connected with earth.

(viii) Where an alternating-current system having a point connected with earth (whether electrically interconnected as aforesaid with another system or not) is used for affording a supply of energy at low or medium voltage to an electrode boiler which is also connected with earth, the following conditions shall have effect:—

(*a*) The metalwork of the electrode boiler shall be efficiently connected to the metal sheathing and metallic armouring (if any) of the electric line whereby energy is supplied to the electrode boiler.

(*b*) The Undertakers shall serve a notice on the Postmaster-General at least seven days prior to the date on which such supply of energy is to be afforded, specifying the location of every point (including the earth connection of the electrode boiler) at which the system (including any interconnected systems) is connected with earth.

(ix) Except as hereinbefore provided, it shall not be permissible for the Undertakers to connect any system or interconnected systems with earth at any further point unless such additional connection with earth is for the time being approved by the Electricity Commissioners with the concurrence of the Postmaster-General and is made in accordance with the conditions, if any, of that approval.

Electric Lines, Systems, and Apparatus for High Voltages

Connection with earth.

8. The following provisions shall apply to the connection with earth of systems for use at high voltage:—

(i) Unless otherwise allowed by the Electricity Commissioners and subject as hereinafter provided, a point of every such system shall be connected with earth.

(ii) The connection with earth shall, subject as hereinafter provided, be made at one point only in each system and the insulation of the system shall be efficiently maintained at all other parts.

(iii) In the case of a system as aforesaid comprising electric lines having concentric conductors, the external conductor shall be the one to be connected with earth.

(iv) Where the Undertakers propose to connect with earth at one point only an existing system for use at high voltage which has not hitherto been so connected with earth, the Undertakers shall give notice and particulars to the Postmaster-General of the proposed connection with earth and such notice shall be deemed to be a notice of works served upon the Postmaster-General within the meaning and for the purposes of Section 14 of the Schedule to the Electric Lighting (Clauses) Act, 1899, or corresponding provision in any Act or Order relating to the undertaking of the Undertakers.

(v) Where a system having a point connected with earth is used for affording a supply of energy at high voltage to an electrode boiler which is also connected with earth, the following conditions shall have effect:—

(*a*) The metalwork of the electrode boiler shall be efficiently connected to the metal sheathing and metallic armouring (if any) of the high-voltage electric line whereby energy is supplied to the electrode boiler.

(*b*) The supply of energy at high voltage to the electrode boiler shall be controlled by a suitable automatic circuit-breaker so set as to operate in the event of the phase currents becoming unbalanced to the extent of 10 per cent of the rated current consumption of the electrode boiler under normal conditions of operation:

Provided that if in any case a higher setting is essential to ensure stability of operation of the electrode boiler, the setting may be increased to but shall in no circumstances exceed 15 per cent of the rated current consumption of the electrode boiler under normal conditions of operation.

(c) An inverse time element device may be used in conjunction with the aforesaid automatic circuit-breaker to prevent the operation thereof unnecessarily on the occurrence of unbalanced phase currents of momentary or short duration.

(d) The Undertakers shall serve a notice on the Postmaster-General at least seven days prior to the date on which such supply of energy is to be afforded specifying the location of every point (including the earth connection of the electrode boiler) at which the system is connected with earth.

(vi) It shall not be permissible for the Undertakers to interconnect electrically systems for use at high voltage which are each connected with earth at one point, or, except as hereinbefore provided, to connect any such system with earth at more than one point, unless electrical interconnection as aforesaid or connection with earth at more than one point is for the time being approved by the Electricity Commissioners, with the concurrence of the Postmaster-General, and is made in accordance with the conditions, if any, of that approval.

Electric Lines and Apparatus (General) other than Consumers' Installations

(b) Any metalwork enclosing, supporting or otherwise associated with electric lines and apparatus unless designed to serve as a conductor shall where necessary to prevent danger be connected with earth.

Supply to Premises of Consumers: Consumers' Installations

*Supply at medium voltage.**

29.—(a) The Undertakers shall not be compelled to commence or, subject to the provisions of Regulation 32, to continue to give a supply of energy at medium voltage to any consumer unless they are reasonably satisfied in respect of the consumer's installation—

(i) That all metalwork enclosing, supporting or associated with the consumer's installation, other than that designed to serve as a conductor, is where necessary to prevent danger connected with earth.

Overhead Line Regulations for Securing the Safety of the Public, made by the Electricity Commissioners under the Electricity (Supply) Acts, 1882 to 1928 (*Reproduced by permission of H.M. Stationery Office*)

B. For voltages *exceeding* 650 volts direct current and 325 volts alternating current.

Provision to prevent danger.

17. Adequate means shall be provided to render any line conductor dead in the event of it falling due to breakage or otherwise.

All metalwork other than conductors shall be permanently and efficiently connected with earth. For this purpose a continuous earth wire shall be provided and connected with earth at four points in every mile, the spacing between the points being as nearly equidistant as possible, or, alternatively, the metalwork shall be connected to an effective earthing device at each individual support. The design and construction of the system of earth connections shall be such that when contact is made between a line conductor and metal connected with earth the resulting leakage current shall not be less than twice the leakage current required to operate the devices which make the line dead.

* Practically the same regulation applies to high-voltage installations.

Extract from I.E.E. Regulations for the Electrical Equipment of Buildings, Eleventh Edition (June, 1939)

Metal required to be earthed.

1001. (A). Except as specifically exempted in the following Exemptions (i) and (ix), all metalwork of the electrical equipment, other than current-carrying parts, shall be earthed.

Exemptions.—(i) Metal in earth-free situations (see Definition) other than runs of metal conduit and the close-fitting metal sheathings and armourings of cables. (Such conduit, sheathing, and armouring, have always to be earthed.)

(ii)–(ix). Detailed exemptions of less importance than (i)—see Regulations.

Systems of earthing.

1005. (A). Every earthing lead shall be connected to an earth electrode, and every endeavour shall be made to render the "consumer's earth resistance" low enough to permit the passage of the current necessary to operate the fuse or the overload trip of the circuit-breaker protecting the circuit.

(B). The electrical resistance of the earth continuity conductor, including metal conduits, the metal sheathing of cables (other than those used in earthed concentric wiring), and the armouring (where an armoured cable has no other metal sheath), together with the resistance of the earthing lead, but excluding the resistance of the earth-leakage circuit-breaker (if any) shall, when measured from the connection with the earth electrode to any other position in the completed installation, not exceed 1 ohm.

Earth-leakage protection.

1006. Except as specifically exempted in the following Exemptions (i) to (iii), earth-leakage protection shall be provided in all installations and shall be capable of disconnecting the live conductors of the whole installation or, if desired, of only the faulty circuit (or circuits) when the potential between the metal to be protected and earth exceeds 40 volts. Such earth-leakage protection shall be in the form of one or more automatic devices operating on the existence of a potential between the metal to be protected and earth, or alternatively, equivalent devices responsive to leakage currents between such metal and earth. Such automatic devices may, if desired, be incorporated with excess-current protective devices.

Exemptions.—(i) Where the maximum possible earth-leakage current from a circuit can be proved to be greater than the overload value at which the fuse or circuit-breaker is set to operate.

NOTE.—For the purpose of this exemption the maximum earth-leakage current may, if desired, be computed on the assumption that the only resistance in the circuit is the "consumers' earth resistance" (see Definition).

(ii) Where the current rating of the fuse or circuit-breaker controlling the circuit does not exceed 100 amperes and the metalwork of the installation is earthed to an urban system of underground metallic water mains having metal-to-metal joints (it being permissible to assume that the maximum possible earth-leakage current will then be sufficient to operate the said fuse or circuit-breaker).

NOTE.—Where earth-leakage protection is provided by means of a circuit-breaker operated by rise of potential, the tripping solenoid of the circuit-breaker may be connected in series with the earth continuity conductor, and, as an alternative method, direct earthing may, if desired, be provided in addition.

APPENDIX 2

Typical Soil Resistivities Measured by the Electrical Research Association

Resistivities are mean values to a depth varying from 2 ft. to 8 ft.

Soil	Resistivity, ohm-cm.	Locality	
Clay ..	2 000–2 700	Stowmarket, Suffolk	
Clay ..	500–1 700	Cuffley, Herts	
Clay ..	400–1 000	Alperton, Middlesex	
Brick clay	2 600–2 800	Enfield, Middlesex	
Hard clay	5 000–15 000	Hastings, Sussex	
Chalk ..	9 000–14 000	Thetford, Norfolk	
Chalk ..	6 000–12 000	Stevenage, Herts	
Chalk ..	14 000–15 000	Welford,	Berkshire and Hampshire
Chalk ..	18 000–30 000	Easton,	
Chalk ..	9 000	East Shefford,	
Chalk ..	11 000–13 000	East Garston,	
Chalk ..	11 000–40 000	Belmount,	
Chalk ..	26 000–35 000	New Barn Farm,	
Chalk ..	16 000–20 000	Balldown,	
Chalk ..	10 000	White Wall Spur,	
Chalk ..	14 000	Barrow Hill Spur,	
Sand ..	9 000–19 000	Coddenham, Suffolk	
Sand ..	17 000	Blythburgh, Suffolk	
Sand ..	40 000–45 000	Wenhaston, Suffolk	
Sand ..	57 000–68 000	Reydon Mount Pleasant, Suffolk	
Sand ..	12 000–18 000	Reydon Village, Suffolk	
Sand ..	57 000–88 000	Southwold, Suffolk	
Sand ..	53 000	Bulchamp, Suffolk	
Sand ..	300 000–800 000	Newchurch Common, Cheshire	
Marsh ..	220–270	Blythburgh, Suffolk	
Peat ..	20 000	North Wales	
Rocky mountain area	100 000	North Wales	
Sandy gravel	30 000–50 000	Riding Mill, Northumberland	

APPENDIX 3

Example of the Design of a Neutral-Point Earth Electrode

It is required to design an earth electrode for the neutral point of a system fed by a 1 500-kVA, 6 600-volt, 3-phase transformer. The earth-fault protective gear is of the inverse time-limit type, and is set to operate in 10 seconds at twice full-load current. The resistivity of the clay soil is 2 500 ohm-cm.

Full-load current = 131 amp.

Let A = total surface area of electrodes, in sq. in.
i = current density on surface of electrodes.
t = time to failure of electrodes, in seconds.

Then, substituting in the formula $t = 2\,400/(i^2\rho)$, we have

$$10 = \frac{2\,400}{\left(\frac{262}{A}\right)^2 \cdot 2\,500}$$

Whence $A = 843$ sq. in.

Since the surface area of a $\frac{1}{2}$-in. dia. copper rod 8 ft. long is 150 sq. in., six such rods will be required to provide a satisfactory electrode. The resistance of these rods if they are spaced more than 8 ft. apart will be 9·5 ohms, and the total resistance of the six in parallel about 1·6 ohms.

APPENDIX 4

Resistance of Strip or Conductor Electrodes

Where the soil resistivity is appreciably lower at the surface than at a depth it is preferable to use strip or conductor electrodes. By this means it is possible to secure low values of resistance in soils of quite high resistivity, and details of some actual results which have been obtained in rural areas in England are given below.

Resistance of Strip or Conductor Electrodes

Site	Resistivity, ohm-cm.	Length of strip, in feet	Resistance measured
Stowupland ..	1 910	83	1·5
Sturton Road, Diss	1 590–2 140	120	2·75
Coddenham ..	9 550–11 300	255	3·6
Reydon Village and Hall	17 950-12 200	873 in the form of a grill	3·5
Welford	15 500	279	6·0
Easton	[18 700* / 30 400]	324	2·95
East Shefford ..	8 680	348	2·0
East Garston ..	12 800	211	3·0
Belmount ..	[11 300* / 40 000]	384	3·5
New Barn Farm..	34 400	405	6·0
New Barn Farm..	27 500	819	3·9
Balldown.. ..	20 000	450	4·8
White Wall Spur	10 500	450	3·5
Barrow Hill Spur	13 800	360	3·0

* These two values were taken in different parts of the site.

The results are also shown diagrammatically in Fig. 4, which indicates that the practical values correspond reasonably well with the theoretical values—divergences therefrom are due to variation of resistivity with depth and along the length of the electrode.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 14TH FEBRUARY, 1940

Mr. F. H. Sharpe: My remarks will be chiefly confined to the large-power high-voltage aspect of this subject. I am surprised to find that the word "bonding" is not mentioned in the paper: in heavy-current engineering "bonding and earthing" rightly is a term in common use; the two words are complementary.

The authors mention as typifying the very latest practice "the proposal to install eight 32 ft. × ½ in. diameter copper rods at a Central Electricity Board substation to secure a resistance of less than 1 ohm, in soil having a resistivity, near the surface, of 15 000 ohm-cm." It may be of interest to give the results obtained with this installation. We found the conditions on this 132-kV substation site such that finally 16 rods were driven, varying from 4 ft. to 24 ft. in length. The lowest resistance was 12·9 ohms and the highest about 100, giving a final figure with all the rods in parallel (we were justified, I think, in assuming that their resistances could be dealt with in that way) of 1·5 ohms. To obtain comparative data the Board agreed to put in earth plates as well as rods at this site, and the two plates installed gave earth resistances of 16·2 and 16·7 ohms. On this showing the rods seem to be very successful. A most interesting point is that when we measured the earth resistance of the substation as a whole, with all the rods and plates disconnected, we found it was only 0·5 ohm. We thought first of all that the explanation might lie in the earthing effect of the various copper connections running down from the structures to the earth plates and rods, but as these were taped such an explanation was ruled out. The very low value of earth resistance can therefore be attributed only to the inherent earthing property of a large reinforced-concrete foundation in the ground. Such a property may be rather a nuisance in other cases, for instance in connection with frame-leakage busbar protection, where the switchgear has to be insulated from earth, or rather, earthed only through a selected path. An earth-resistance figure where the concrete was relied on for insulation, which may be of interest, is that of 0·5 ohm which was obtained for a large 33-kV metalclad switchboard installed in a properly heated switch-house. Earth-resistance measurements have recently been taken on a 25-mile line with about 150 towers, and we found that about 17 % of the towers had footing resistance of over 100 ohms, the values mostly lying between 10 and 20 ohms. In the light of such information as this it is questionable whether the present regulation about earthing every fourth tower is not rather stringent, and likely to involve unnecessary expense. It may also be an encouragement to break the regulations.

We are rather optimistically told in Table 7 that "Each tower should have such an earth resistance that flash-over from tower to lines cannot occur with maximum possible lightning current." A method which is being adopted for lightning protection in the case of the grid is to provide two earth wires for the last mile run-in to a substation.

I do not entirely agree with the authors' statement, dealing with the earthing of high-voltage overhead-line supports, that "The electrode earthing the continuous earth wire and the metalwork of a transformer should be kept well away from the l.v. system earth." Some years ago Swiss engineers, in discussions on the international transformer specification,* advocated increasing the test voltage on transformers, particularly lower-voltage transformers, and pointed out that very high voltages could be obtained on the l.v. side due to high-voltage earth-fault current passing through the same earth plate as is used on the low-voltage system. The views of the delegates of the other countries represented agreed with that of Great Britain—that we wanted, not to increase the test voltage on the transformer, but to stop the voltage getting there, and improvement in earth resistance was essential. There was difference of opinion between nations as to whether the two earths should be coupled together; my own opinion is that separation of earthing in itself is not the solution. It is necessary to have as low an earth resistance as possible, to study the probable route of the fault current from any faulty apparatus via earth paths back to the neutral of the transformer, and to make this path as direct as possible —without need for the fault current to loop round via branch connections in the station copper earth bars. In small low-voltage pole-type substations the matter is perhaps not of great importance, but when one is dealing with two 45 000-kVA transformers of, say, 6·6 kV the earth-fault currents may be tremendous, even when limited by resistors, and the planning of the earthing system is a very complicated job. It is not possible to say, for instance, that by separating the low-voltage and high-voltage earths we can avoid voltage-rise; the only thing to do is to bond everything as adequately as possible to a main and common earthing system, using one's discretion how the bonding is done so that current is encouraged to take direct paths to the earth plates or rods. The above appears paradoxical, but is not really so. Perhaps the authors will give their views on the matter.

I agree with them that the cables on a supply system usually form the best earth. A few years ago it was established as the result of investigation of slight corrosion troubles that the best reference datum for earth in the East London area was provided by the Central Electricity Board's cables running into London. I think that from the earthing point of view cable systems are at least as valuable as water pipes.

If we have cables interconnecting two points where we know that earth-fault current will some day flow, we have to consider whether their lead sheaths are adequate to take the current; we may have to supplement them by an additional run of copper. Alternatively, if we have plenty of lead we have to decide whether to bond all the sheaths together so as to avoid such troubles as inter-sheath pitting, or whether to insulate them from each other. If we insulate them, we are faced with possible danger to life through voltage-rises. It is disappointing that the paper does not deal at greater length with this side of the subject.

I have been under the impression hitherto that neutralizing is illegal in Germany and also in this country. I should be glad to have confirmation of this. If a

* "Rules for Electrical Machinery" (I.E.C. Publication No. 34).

reliable earth cannot be obtained, I prefer earth-leakage circuit-breakers to protective multiple earthing.

I notice that on page 360 it is stated " If, on the other hand, it is possible economically to get the neutral resistance to earth to such a low figure that protective multiple earthing will be absolutely safe in all conceivable circumstances, then it will be unnecessary to use this system because ordinary earthing should prove quite satisfactory." On page 361, however, the authors remark " Under severe unbalanced loads the rise in potential of the neutral is not serious, and it can be said definitely that a protective multiple earthing system under normal working conditions is much safer than a system earthed in the usual way." These statements do not seem to be properly related one to the other.

I am interested to see the use of coke for earthing purposes coming back into fashion again, and to note what good results can be obtained by means of salt. There are very many cases—large substations, for example—where one can afford to spend a few extra pounds on salting and can dig up the earth connection a few years later to make sure it is still efficient. Would it be an advantage to place the earth electrode in a metal container so as to stop the washing-away of the salt?

It will be remembered that in the early days of the grid, when we were experimenting with pole foundations, a tool was employed which bored a hole and then made a conical undercut in the soil. It seems possible that such a tool could be applied in connection with earthing. The hole having been drilled and undercut, it would be filled with salt and a tube would be driven in. I should like to know the authors' opinion of this idea.

Under the heading " Strips and Conductors " (page 366) it is stated that the copper strip should preferably be untinned. What is the reason for this?

Very little reference is made in the paper to the great importance of mechanical security of all the copper-work external to the electrodes. Protection should be afforded not only against corrosion but also against the effects of mechanical stresses. Flashover, or failure of a neutral resistor, immediately permits very high values of fault current, and the copper connections should be designed with the corresponding thermal and electromagnetic effects in mind.

(*Communicated*) It is my understanding that the idea of neutralizing originated in Germany, but the translation of the German term *nullung* by the word " neutralizing " is misleading because what the Germans understand by *nullung* is what we understand by protective multiple earthing, at least as applied to overhead distribution systems.

Earthing of the neutral at one point only, accompanied by connection of non-current-carrying metal parts to this neutral, is not permitted in overhead networks in Germany; indeed, the local earth called for at the end of every spur line must have a resistance at least as low as 5 ohms.* The authors' proposal to earth the neutral in the way implied by their term " neutralizing " is to my mind unsafe, even if one adopts the precautions in line design and earth guards to which they refer.

Mr. J. S. Forrest: I shall confine my remarks to the earthing of high-voltage transmission-line steel towers.

In the paper there is a reference to the necessity of obtaining low values of earth resistance, and it is fortunate that such values can easily be obtained in most parts of this country. Recently the Central Electricity Board has made a practice on new lines of measuring the footing resistance of every tower before the line goes into service, and many valuable data are now being accumulated. It may be of interest to give a few examples of these measurements.

In Fig. A is shown the distribution of tower footing resistances on the Percival Lane–Chester line in N.W. England. Over 90 % of the towers have a footing resistance of less than 5 ohms, and none has a resistance of more than 15 ohms. The tower foundations are in

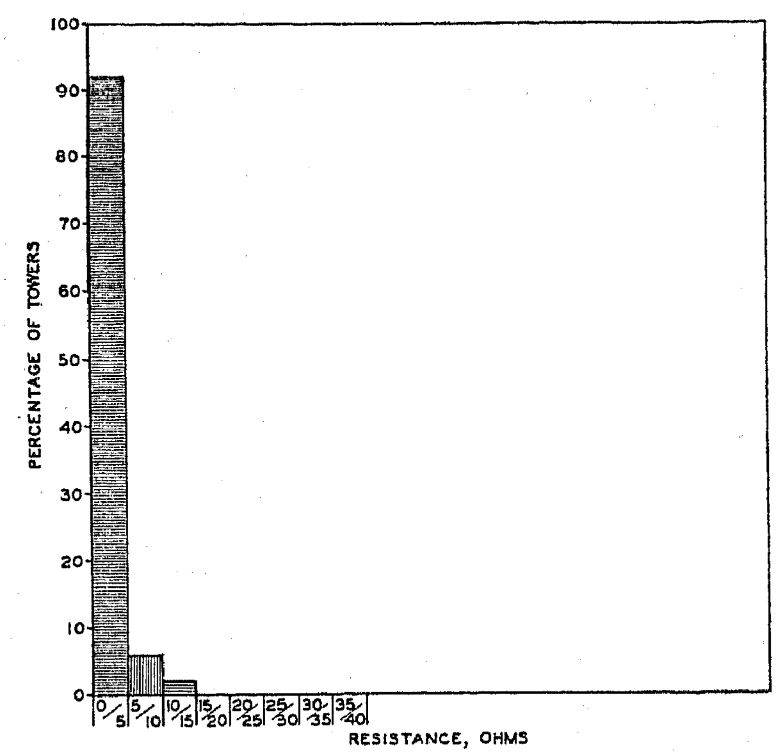

Fig. A.—Distribution of tower footing resistances on Percival Lane–Chester 132-kV line.

clay, but such low values are typical of many lines in this country.

Fig. B shows the distribution of footing resistances on a line on the South Coast, the line to which Mr. Sharpe referred. The resistances are rather higher in this case, the mean value being about 10 ohms. No tower has a resistance of more than 20 ohms, so that from the point of view of lightning protection the position is quite satisfactory. The foundations are in chalk, and these results are typical of chalky soil.

Fig. C gives the distribution of footing resistances for a line in South Wales, in mountainous, rocky country. The earth resistances are very high, values of from 10 to 60 ohms being quite common, while one tower has a value of 175 ohms. The foundations are in carboniferous limestone rock, and it is fortunate that there are not many other such cases in this country.

The measurements to which I have referred have also shown that the conventional earth pipe has a negligible effect in reducing footing resistance. If the resistance is high, it is necessary to install an extensive earthing system of the counterpoise type. On new lines we are

* See *Elektrotechnische Zeitschrift*, 1939, **61**, p. 1282.

discontinuing the use of earth pipes on steel towers and are making measurements of footing resistance to determine whether the resistances are sufficiently low.

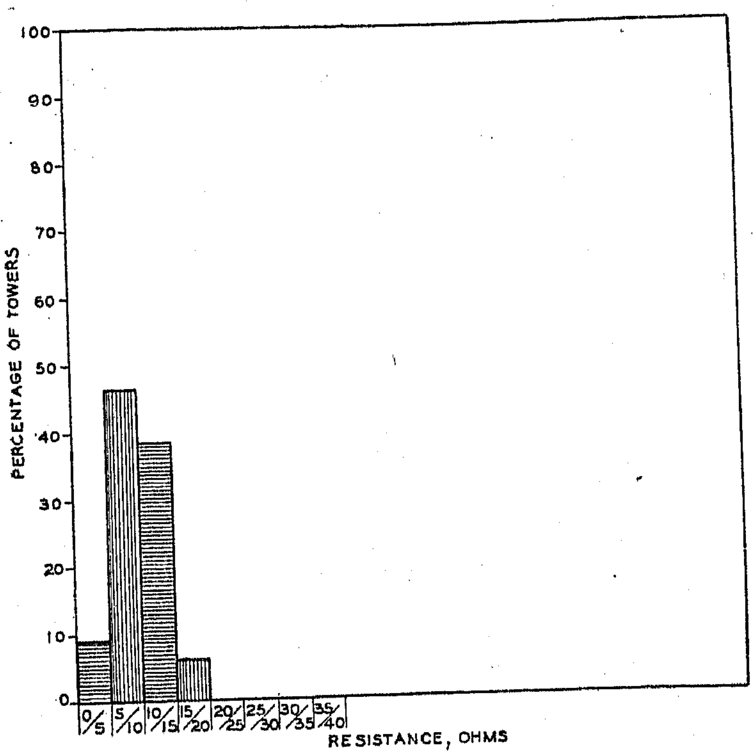

Fig. B.—Distribution of tower footing resistances on Brighton–Worthing line (No. 3).

I agree with the authors that the secular and seasonal variations of earth resistance which are experienced are not very large. We find that variations of more than 2 : 1 are uncommon.

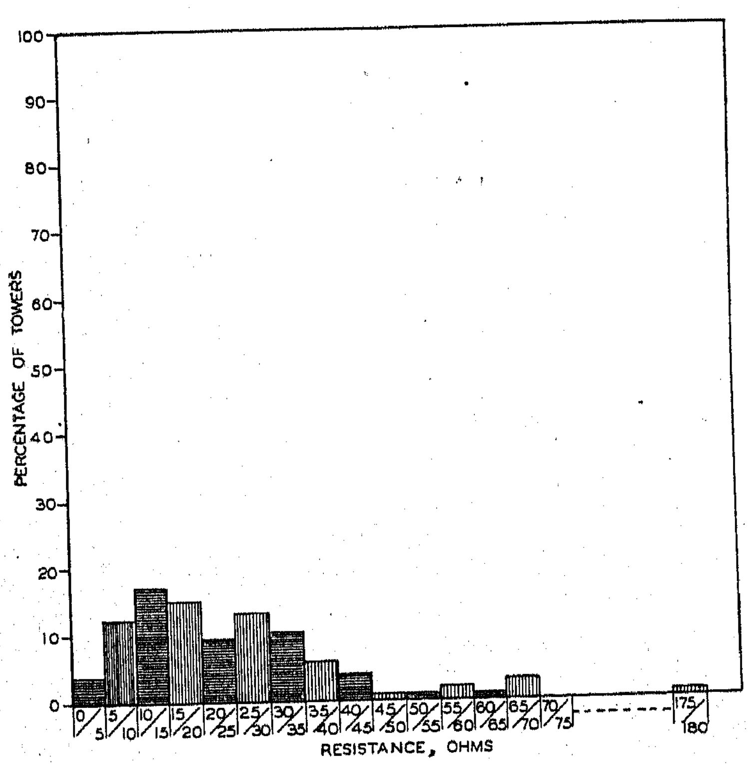

Fig. C.—Distribution of tower footing resistances on Upper Boat–Ebbw Vale 132-kV line.

With regard to the method of measuring tower footing resistances on steel towers with a continuous earth wire, we find that the field testing personnel usually prefer to disconnect the earth wire rather than to use one of the more complicated methods which enable the resistance to be determined with the earth wire connected. This is probably the right procedure in the case of a suspension tower, because it is a simple matter to isolate the earth wire from the tower. On tension towers, however, it is a matter of some difficulty to isolate the earth wire, and I should like to have the authors' views as to the practicability of using the more complicated methods on site, bearing in mind that the routine measurements at least have to be made by field testing personnel and not by highly-trained laboratory staff.

Mr. S. W. Melsom: It would be extremely valuable if someone would produce a practical paper telling us what his experience has been with the systems described by the authors.

Some time ago a paper by an engineer from India, Mr. Henshaw, showed that not only in a field where there are cattle but even in a house there may be great differences of voltage between pieces of metal that are earthed at different parts of the system. The author of the paper instanced the case of a water pipe in a room where a switchboard was installed, the water pipe being earthed to the water system and the switchboard to some form of pipe or plate in the vicinity. The resistivity of the soil between the two was so great that quite a high voltage existed between them, and the presence in the same room of these two pieces of earthed metal was a danger rather than a safety measure. Mr. Henshaw got over the difficulty by putting a piece of wood over the water pipe, but a good deal of further work on the subject seems to be called for.

A point of scientific interest in the paper is the effect of long-duration loading on an electrode. When there is presented to a plate or driven pipe electrode rather more current than it can conveniently carry, a temperature rise occurs in the vicinity of the junction of the electrode and the earth; and, since these leakage currents appear to be constant, the earth plate or pipe will cease to function as such and become an automatic current-limiter and thermostat.

The authors dismiss the subject of earth-leakage circuit-breakers after very brief consideration; but I feel that there is urgent need for a paper on the subject to be read and discussed before this Section.

One of the earliest definitions of earthing was "Means to be taken to ensure the immediate and safe discharge of the electrical energy to earth in the event of the insulation being defective." The point to be remembered in this connection is that the early insulation was bad. Not only was there a lack of materials such as are now available, but the design of the insulators was not so good as it is to-day. Thus it was general practice to regard insulation as likely to break down. If insulating materials had been perfect from the start we should never have heard anything about earthing, because it would not have been necessary.

In considering the question of general safety, of which earthing is only a part, we must remember that there has been an enormous advance in the art of insulation. For many problems in connection with low-voltage supply I believe that insulation and not earthing is the real solution. I do not want to say that earthing is unnecessary in any case, because that would be incorrect; but I feel that a real discussion of the problem of safety requires consideration of insulation, and that it is high time that

we had a comprehensive paper, such as this one is, dealing with insulation.

Mr. T. C. Gilbert: I am glad to see that the paper deals with the very important matter of current loading of earth electrodes, and shows that the current loading can be improved by appropriate treatment of the electrodes. In this connection I am unable to understand the authors' preoccupation with coke, in view of the fact that coke treatment is prohibited in practically every country in the world. I should like to ask why no consideration has been given to the use of crushed carbon or charcoal, which possesses the advantages of coke but is not liable to cause electrode corrosion.

An interesting case is made out for a new type of long electrode, driven to what are, for this country, unusual depths in order to reach conductive strata. I find myself unable to place any reliance upon the authors' theoretical conductance curves, as it is found in practice that the behaviour of any individual electrode under current loading is impossible to forecast; this is borne out by the practical tests recorded in the paper.

Independent American reports upon the use of long electrodes seem to indicate that some difficulty is encountered in practice with the joints. Obviously these long rods cannot be driven in one length, and there are only two methods of jointing. One is the use of an internally screwed dowel of considerably less diameter than the rod itself—in the case of a $\frac{1}{2}$-in. rod the threaded dowel cannot be larger than $\frac{1}{4}$ in. These joints are found to be mechanically weak; also, for all purposes of current loading and resistance to corrosion the effective diameter of the $\frac{1}{2}$-in. rod is only $\frac{1}{4}$ in., and it cannot be expected that the joint will remain tightly screwed under the vibration necessary to drive it to considerable depths.

The alternative method of jointing, by externally threading the rod and using an oversize coupling, has the effect of enlarging the hole into which the electrode is driven, with consequent increase in earth resistance. Early experiments with long driven electrodes showed that in some cases an unexpected increase in resistance occurred with deep driving. This was explained by stating that a sudden bend had occurred at a weak joint, resulting in the parting of the rod, with the fractured end starting off in a new direction. Some of Mr. Taylor's published records have indicated this tendency.

I question the authors' view that an electrode of 3 ohms resistance can be secured by means of driven rods on consumers' premises at a cost of only 8s. If the full cost of skilled designing, etc., is taken into account, the provision of a permanent 3-ohm electrode will probably be nearer £8 than 8s., even if no larger apparatus than a cooker is installed.

On page 361 it is stated that a practical difficulty associated with the use of earth-leakage circuit-breakers is unwanted operation due to boiling-plate leakages. This disability was impressed upon the earth-leakage circuit-breaker by reason of the 30-mA requirement contained in the Tenth Edition of the I.E.E. Wiring Regulations. As this requirement has been omitted from the Eleventh Edition, and operation placed upon a voltage basis, the difficulty no longer exists, unless the leakage reaches 50 or 60 mA, when I suggest that the boiling-plate *should* be isolated.

The requirements for the ideal electrode are in themselves contradictory. For instance, to prevent surface gradients the rod or plate must be deeply buried and an insulated lead connected to it; on the other hand, reliability requires that any connection to an electrode should be above ground, and open for inspection. The enclosing of the electrode top in insulating tubing is not a cure for surface gradient in all cases, as this gradient may appear at some point remote from the electrode—in a pond or on the surface of specially conductive soil. Animals have been killed in this country by such voltage gradients.

A recent Home Office publication* calls attention to the difficulty, if not impossibility, of providing for proper earthing in the interior installation. In this connection I understand that the Electrical Research Association are to investigate the question of the conductivity of conduit joints, it being found impossible in many cases to conform to the 1-ohm requirement.

I agree that a well-planned and constantly-attended electrode cannot perform its proper function unless all fuses, whether in the interior installation or at the substation, are properly graded—a condition which does not exist in the majority of cases. As the output from rural transformers may be restricted by proper attention to these points, it is clear that electricity supply is becoming dependent upon its protective systems instead of seeking alternative methods, which have been adopted elsewhere, mainly upon a voltage basis and in which Nature herself does not play such an overriding part. My impression is that the paper has not taken us much farther than the position which existed 10 years ago when my book† was written. The practical efficiency limit of electrodes has been reached and passed, and protective methods must now be found that are not completely vitiated by seasonal rains or frosts and that are, above all, independent of the circuit fuses.

Mr. J. F. Shipley: The authors' suggestion that engineers should use geological drift maps seems to be a good one, but these maps should be used with care as they are always made on a very large scale.

With regard to the subject of rainfall, that in this country is very satisfactory from the point of view of earthing; it is very generous all the year round, but not too generous. In some countries of which I have had experience the annual local rainfall is 400 in., and it nearly all occurs within 2 or 3 months. The rain is so heavy that it sometimes washes the earth connection away completely. The rain water is itself of very low conductivity, and as it falls in such quantity it acts as a leaching agent and washes all the conducting salts out of the soil; so that although the soil is soaked with water in the wet season it is still a bad conductor.

I should like to quote a few figures bearing on this point. The condensate in a modern turbo generating station has a conductivity figure (the reciprocal of megohms per cm. cube) of about 2. London rain water has a conductivity figure of about 390, and Glasgow water of about 119. Manchester water, one of the softest on record, has a conductivity figure of 48, and sea water a figure of 50 000. In the case to which I am referring

* "Electrical Accidents and their Causes, 1938."
† "Artificial Earthing for Electrical Installations" (London, 1932).

we found the conductivity of the water to be of the order of 18; and that was after 6 months' storage in a reservoir, and a 5- or 6-mile journey along a river bed. I estimate that the original conductivity figure was about 10. When, therefore, heavy rainfall occurs in atmospheres that are comparatively free from dust and pollution, the rain water is an almost perfect insulating material. I found this out in a practical way by trying to test a 6·6-kV alternator on a testing tank. I used ordinary water from the hillside and found that I could put 6·6 kV on the water with electrodes 3 ft. apart without the slightest sign of current passing between the electrodes.*

I read of a case recently where considerable damage was done by lightning to a lead-covered cable in the dry climate of S. Africa. The cores were repeatedly damaged by discharges within the cable which coincided with lightning strokes that struck the ground some distance away. In this country we are accustomed to think that if lead-sheathed cable is buried in the earth the conductor inside is safe from external discharges, but this incident shows that that is not the case. I understand that owing to the dryness and high resistivity of the soil the earthing which was secured by the cable being buried was insufficient; and the cable is now being additionally earthed at intervals by pipe earths.

Mr. P. B. Frost: Protective multiple earthing has gone a long way towards securing safety for consumers in the circumstances for which it was introduced—that is to say, rural areas, high-resistivity soils, overhead-line distribution and scattered loads. We cannot pretend, however, that we have yet overcome the difficulties and the dangers that arise from a broken neutral or from a heavy earth fault on one phase. Either of these conditions where protective multiple earthing is in use, will lead to a large amount of consumers' apparatus, which is supposed to be protected, being at a dangerous potential difference from earth for a considerable period of time.

The authors do not mention the possible improvement of the protective multiple earthing arrangement which can be obtained by splitting the neutral. The use of a split neutral with some sort of cross-lacing between the two wires will ensure (1) that a neutral will never be broken unless, say, a tree falls right through the line and breaks all the wires; and (2) that a phase wire in falling will be certain to make contact with the split neutral. The improvement in the protective multiple earthing arrangement due to employing a split neutral will be increased if the recommendations contained in the footnote on page 360 are adopted in addition. The resulting arrangement will be fairly safe but will be costly; and on the score of cost many engineers will probably prefer to use the earth-leakage circuit-breaker arrangement.

With regard to Table 7, in the section "Tramway system earth" it is stated that the technical points to be considered are the relation between the area of the electrode and the fault current, and the question of catering for system faults and consumers' faults. Neither of these, however, properly concerns the earth plate of a tramway system, whose primary function is (*a*) to enable an indication to be given of the current which leaks from the rails and finds its way back through the earth to the negative busbar, and (*b*) to help to clear faults on the system; I therefore hope that Table 7 will be amended.

Mr. Shipley will be interested to know that telephone cables are damaged by lightning in this country as well as in Africa. We have encountered several such cases; in one fairly recent case a long main underground cable not connected in any way with overhead lines developed about 10 faults distributed over some miles due to lightning discharge between the sheath and the conductors.

Mr. G. W. Preston: Driven earth electrodes are particularly advantageous in cases where it is necessary to make the earth connection after the structural work has been finished. The driven rod has the advantage that it can be installed close to a foundation, at the foot of a brick wall or even through the basement floor of a finished building. Earth rods have actually been installed through the concrete floors of buildings, and I myself have installed such a rod for my own use in the middle of a lawn with very little surface disfigurement.

Mr. Gilbert referred to the driving of long rods and to difficulties which have been met with in America in making the necessary joints. In this country we have endeavoured to design joints the outside diameter of which is the same as that of the rod. Such joints do not open out the hole as the rod is driven and do not give rise to an increase in resistance. Their mechanical strength has also proved to be quite satisfactory.

Mr. P. J. Higgs: Recently some iron plates were unearthed after having been buried horizontally in sandy loam for about 14 years. The plates buried 6 ft. deep were corroded (rusted) only superficially; those buried 3 ft. deep were corroded to a somewhat greater extent. The greater corrosion of the plates at the smaller depth was possibly due to their having been the more directly exposed to the air and water which penetrated into the ground from the surface. The earthing resistance of one plate buried 6 ft. deep varied originally during one year from 8·1 to 10·5 ohms; just before the plate was unearthed the resistance was 7·5 ohms.

Iron corrodes at a certain rate when exposed to moisture and at a greater rate if copper is present. On page 371, reference is made to tests to determine the comparative corrosions of iron and copper specimens buried near together in the ground. The question arises whether the results are likely to be representative for the iron.

In order to understand the reasons for the variableness of earthing resistances, one should appreciate that earth conductivity is essentially electrolytic in nature, being due to the matter dissolved in the moisture contained in the soil. Dry earth and pure water are insulators. As an example of such variableness the results shown by Fig. 15 may be referred to; the peculiar resistance-changes shown are probably caused by the direct current dissociating electrolytically the moisture adjacent

* Since the above statement was made numerous tests have been taken, with the following interesting results:

Water just received from the clouds in a rain gauge, 6 conductivity units. Similar water stored in a reservoir draining a natural catchment area, 15 units. The same water after further transit along two river beds, totalling about 7 miles, and a canal, pipeline and hydro-electric power station, 20 units. The same water after violent disturbance of the river bed by a torrent or by cattle, 65 units (after one day's storage the conductivity drops again to between 15 and 20 units). Maximum conductivity obtained over a period of about 4 months, 65 units.

Thus water from the clouds in a clean atmosphere is equal to or better than any distilled water purchasable commercially in the United Kingdom.

to the electrode surface, for the resistance would increase as the gas bubbles form and decrease as they disperse.

The results shown by Fig. 4 confirm that the actual earthing resistances can differ greatly from the calculated values. I have tested two similar pipes driven into the ground a few feet apart; the earthing resistance of one was about 30 ohms and of the other about 60 ohms. This indicates that, while theory may be useful as a guide in installing electrodes, final dependence should be placed on test.

I desire to add a few words in support of the bonding-together of underground metal systems and their use for earthing purposes. I feel that in an urban area, having an extensive network of pipes and cable sheaths, the real " earth " of the district is the network and that, in any case, the network carries a large proportion of the earth currents. That part of the current (normally small in relation to the whole) which flows from metal to soil or vice versa is the one which causes the troublesome corrosive effects. These effects may be minimized by effective bonding of the network. In Table 7 it is recommended that consumers' apparatus be connected to the metal network and that a d.c. system neutral point be connected to a driven pipe or buried plate; this condition is one in which fault currents must flow from metal to soil, the corrosion of the metal being thus increased.

Mr. F. W. Purse: This paper confirms what an eminent engineer once said to me on the question of earthing. He said " Always remember that if you have to choose between a square foot of copper in the ground and that same amount of copper stretched out in as long a strip round the earth as can be managed, choose the long strip."

I must refer to something which Mr. Sharpe and Mr. Higgs have mentioned, the questions of bonding and of the path taken by earth currents. The water supply authorities in this country have always discouraged earthing to water mains, and maintained that each consumer should have his own earth plate. On the other hand, my contention has been that the more earth plates the more damage there would be to water pipes; because where earth plates are installed the current gets into the soil and then on to the nearest water pipe. My opinion was confirmed not very long ago when an eminent water engineer produced for information a piece of water pipe which had been partially destroyed by electrolysis caused by earth currents from a radio receiver. I happened to know the electrical engineer of the undertaking in question, and asked him for the facts. He said that the radio set had its own earth plate which was not far away from the water pipe, and that the pitting of the pipe was the result of the current passing to it through the soil from the earth plate. This raises a question with which I should like the authors to deal: if we adopt their suggestion of using earth plates for high-voltage work and substations, are not we going to get into greater trouble than we should by also earthing to the water pipes where possible?

Mr. R. H. Golde (*communicated*): Mr. Forrest stressed the importance of measuring the tower footing resistance of overhead transmission lines at regular intervals. While it is comparatively easy to carry out this measurement on suspension towers by disconnecting and lifting the earth wire for the short time of the measurement, this simple method cannot be applied to tension towers.

To overcome this difficulty, instead of connecting the earth wire directly to the tower it is possible to insulate it by a normal line insulator (which at the same time takes the strain) and provide the connection to the tower by means of a loop which can be disconnected while the earthing resistance is being measured. The objections to this method are its high cost and the difficulty of adapting it to existing lines. Both these drawbacks are overcome by another method which has been successfully employed on the Continent. As, for the purpose of earthing measurement, it is only necessary to insulate the earth wire from the tower for a few hundred volts, the necessary insulation does not present any electrical difficulties. It is sufficient to place the standard earthing clamp on an insulating plate and surround the fixing bolts to the tower by thin cylinders of insulating material. It is then only necessary to add a loop connection to the tower which can be opened while the earthing measurement is being carried out. The advantage of this method is that the standard earthing clamp for tension towers can be adapted to the new purpose without difficulty.

Mr. J. S. Highfield (*communicated*): The subject of this paper is one in which I have always been very much interested, not only from the point of view of providing satisfactory earths for safety devices but also as regards the rather more difficult requirements when the earth is to be used as a conductor to carry substantial currents.

In 1907 I read a paper on " The Transmission of Electrical Energy by Direct Current on the Series System,"* describing the plant and transmission lines installed by the Metropolitan Electric Supply Co. to initiate the supply in their western area. The transmission system in this case consisted of two underground cables for 100 000 volts, direct current, and an earth return which could be used either permanently by the positive poles of the system being insulated, or, alternatively, as a standby if either of the cables developed a fault. Little was known at the time about earthing, and a complete investigation was made with the object of ascertaining the " best method of adapting the earth as a permanent conductor for industrial currents in such a way as to avoid interference with telegraphs, telephones or other users." The particular points to be ascertained were as follows: (*a*) At what depth below the surface the plates must be buried in order that the effect of currents at or near the surface should be negligible. (*b*) The size and number of plates to be used. (*c*) The distance apart at which the plates should be situated. (*d*) The value of the earth resistance and its degree of constancy.

The answer to (*a*) was that 10 ft. below the surface would suffice for currents up to 20 amperes. With this current passing, the potential difference observed between the surface contact above the earth plate and a point 100 ft. away was 0·024 volt.

As regards (*b*), the test to determine the size of plates showed that with a single plate there was no gain when the current fell below 1 ampere per 600 sq. in. of surface.

Regarding (*c*), the position of plates, there was definite gain between 1 ft. apart and 3 ft. apart; little gain

* *Journal I.E.E.*, 1907, **38**, p. 471.

above 6 ft. apart. The plates at 6 ft. apart show approximately twice the conductivity of plates 1 ft. apart. The plates in clay gave about half the resistance compared with plates in canal water.

The earths as actually constructed consisted in three bore holes, 7 in. diameter and 35 ft. deep, spaced about 40 ft. apart. In each of these a cast-iron pipe was laid with an insulated conductor between the pipe and the surface. At one end of the line the earths were made in clay and at the other end in rather dry gravel.

A steady current of about 90 to 100 amperes was passed between these earths for weeks at a time. The loss in the two earths was 40 to 50 volts at each end, i.e. about 100 volts in all, so that the resistance of each earth was about $\frac{1}{2}$ ohm. It was noted that after heavy rain the resistance decreased. The plates in gravel were rather overloaded when submitted to regular use.

Various forms of earth were used, not only on the Metropolitan system but also in the Isle of Wight and Guernsey. At both these places the supply was direct current at about 3 000 volts. Three cables were used originally, on the 3-wire system. These three cables were used in parallel and connected to the positive supply, the earth being used as a negative.

Various forms of earth were used and an interesting example was one at Cowes, I.O.W., where a shaft about 8 ft. square was constructed. At 15 ft. depth a layer of rock was discovered. Earth plates consisting of cast-iron pipes were driven radially into the blue clay just above the rock. The use of this earth caused serious interference with the local telephones. The shaft was then driven through the rock, which fortunately was only some 5 ft. thick, and the plates driven just below the shelf. These earth plates were used for carrying the whole of the power for several years without causing the slightest interference with the telephones.

The general results set out in the present paper agree very well with those set out above and explained at great length in the paper referred to.

There is just one suggestion, and that is that the copper leads connected to the earth plate should be covered with canvas or protected by rubber to a depth of 6 ft. or more below the ground.

Mr. W. S. Lovely (*communicated*): I suggest that the lead sheaths of buried cables should have been given their place in this paper, as one form of earth plate. My experience during the past 10 years in London has led me to the conclusion that usually cable sheaths are the best earth-plates we have. In fact, I regard them as the main earth connection, to be relied on for carrying return fault current to a station; the usual earth-plates or pipes which one buries in and around a station area I regard as offshoots from the cable-sheath earth, which serve to distribute the low potential of the latter, more or less uniformly, over the site area.

Treating cable sheaths in the manner I have suggested raises the important problem of so making connection between the cable sheaths and the normal-earth copper connections inside a station as to avoid damage to the lead sheaths where the fault current leaves them. Equally too, elsewhere on a cable-run it is essential that the cable sheaths should be so bonded together as to avoid (1) their being damaged by current entering them, and (2) uncontrolled transference of current between sheaths.

It is, I think, to be expected that cable sheaths should carry fault current. The sheath potential plays a controlling part in this matter, and I have usually found that, even where cables run parallel to large water mains, the potential of the cable sheath is negative with respect to that of the water main.

Mr. F. C. Raphael (*communicated*): I am chiefly interested in those parts of the paper which deal with earthing and earth-protection in connection with consumers' installations.

In Table 7 it is stated under (*m*) of col. 4 that for complete protection, the (earth electrode) resistance should be so low that, when it is in series with all the other resistances in the circuit, *twice* the *operating* current of the largest fuse in the installation will flow at the maximum safe voltage; but that this is somewhat relaxed in the I.E.E. Regulations, which only require that this current shall flow at mains voltage. This statement is not altogether accurate. The Regulations referred to are evidently Nos. 1005A and 1006(i). The former requires that every endeavour shall be made to render the "consumer's earth resistance" low enough to permit the passage of the current necessary to operate the fuse or circuit-breaker; and the latter gives the somewhat unsatisfactory rule that the maximum possible earth-leakage current shall be taken. A "Note" is added to explain that this may be worked out on assumption that the only resistances in the circuit are the consumer's earth continuity conductor, his earthing lead and his earth electrode. Thus no account is taken of the resistance of the earth fault nor of the resistance of the substation earth, which may be sufficient in itself to prevent the consumer's main fuse from blowing. On the other hand, the fusing factor should be taken as 1·7 in accordance with B.S. No. 88—1939, and not, as the authors assume, as 2. Nevertheless, one arrives at the same conclusion as is expressed in Table 7, col. 7, namely that unless connection to water mains or cable sheath is possible, the expense of providing a sufficiently low earth-electrode resistance on the consumers' premises is prohibitive except for purely lighting consumers.

It would be useful if the authors could give in their reply some measured values of water-main and cable-sheath resistances in urban areas. We know from experience that the water-main resistances are invariably sufficiently low; and the regulations relieve us from the burden of measuring them in every case. It should, however, be more correct to use the cable sheath as a "cesspool" for our leakage current, which more appropriately should be returned to the electricity undertaking and not to the water supply authority. To conform with regulations, however, we have then to make a measurement of the sheath-to-earth resistance in every case, although on the vast majority of modern or modernized urban distribution systems its low value can be taken for granted.

It would also be interesting to know whether the authors have discovered during the course of their researches why these water-main and sheath resistances to earth are so low. Water mains are insulated with a protective paint, and it is quite possible that it is mainly

the lead service pipes which contribute to the low electrode resistances. But cable sheathing is always protected with at least a heavily compounded serving or hessian tape; does the insulating value of this fall rapidly to zero in ordinary soil, or is the current normally returning through the sheathing to the star point of the transformer at the substation, which will be connected to the sheathing as well as being earthed? From the point of view of blowing fuses, the reason for the low resistances is immaterial, although, on account of voltage gradient, it may be more material to the danger of shock to persons or animals making contact with "earthed" coverings and apparatus. We can go a step further in poorly conductive soils. Any path back from the consumers' cable sheaths or metalclad apparatus to the earthed neutral point at the substation will serve the purpose of blowing fuses. If, therefore, there is a local transformer substation such as the authors describe, and any local water-pipe system or the sheathing of the local distributing system is connected to it, the consumer's "earth" may safely be made to the same pipe or sheathing, even if its actual resistance as an earth electrode is high. This should be permitted by the regulations.

There is one more point to which I should like to call attention. The authors appear to be satisfied with a substation earth resistance of from 3 to 5 ohms. But do not the Electricity Commissioners' Regulations demand something better than this? Admittedly Regulation 4 is carelessly drafted, for it includes a paragraph relating to d.c. supply under the heading of provisions for a.c. systems. As I read the Regulation, a limiting resistance up to 5 ohms is permissible on d.c. supply only if it is normally short-circuited by a fuse or circuit-breaker (the usual practice). Surely the intention of the Regulation is that on a.c. systems there should be a permanent and solid earth of negligible resistance and impedance.

Messrs. E. Fawssett, H. W. Grimmitt, G. F. Shotter, and **Dr. H. G. Taylor** (*in reply*): We are glad to have Mr. Sharpe's very interesting comments on earthing from the point of view of large-power high-voltage installations. His emphasis on bonding is useful, and one can appreciate that with the type of installation referred to this is a matter of considerable importance; and whilst with smaller, lower-voltage installations it is equally important, it does not seem to call for special treatment other than that included under the general heading of earthing.

On at least two Central Electricity Board substations we found the earth resistance to be 0·5 ohm when the rods and plates were disconnected. It is assumed that this is partly due to the extensive amount of reinforced-concrete foundations, etc., but the possibility of overhead-line earth wires being connected-in to the station metalwork should not be overlooked. With steel-tower lines, where a continuous earth wire is bonded to the tower, the tower footings are invariably of lower resistance than the normal type of electrode used, and therefore a strict adherence to the rule of 4 electrodes per mile is unnecessary; we are glad to note from Mr. Forrest's remarks that this practice has been discontinued on C.E.B. steel-tower lines. We are aware of one line which first traverses a sandy area where the resistance of the tower footings has any value up to 100 ohms, and subsequently traverses a clay area where the resistance is as low as 2 ohms. Despite this fact, earth electrodes are still provided at every fourth tower, whereas clearly they are useless in the clay area, and something very much more extensive is necessary in the sandy area.

The occurrence of high voltage on the low-voltage side of a transformer through the earthing system is due to two factors: one, the product of the fault current and the impedance of the high-voltage earth; and the other, the position of the low-voltage earth with respect to the high-voltage earth. If the former is within the resistance area of the latter then it will take up the appropriate voltage corresponding to its position. To avoid this being a dangerous value there are three possible solutions, either to increase the separation or reduce the resistance of the high-voltage electrode, or to reduce the value of the fault current. If a fault occurs in the substation the path back to the neutral of the transformer should be entirely a metallic one, and the earth resistance will not enter into consideration. If, on the other hand, the fault is outside the substation then the current returns by the earth electrode. It is not obvious that one can do much to determine the route of the fault current. Possibly Mr. Sharpe has in mind the avoidance of abnormal stresses, or fusion with small-size conductors, when he refers to the avoidance of indirect paths by branch connections.

In our view, separation of high-voltage and low-voltage earths is a sure preventive of voltage rises on the low-voltage side due to high-voltage faults. With regard to the difficulties encountered when lead cable-sheaths are used to conduct fault currents, it would seem that bonding is preferable to insulation because it avoids both intersheath pitting and possible dangerous voltages. With single-conductor cables the problem is rather specialized; it is treated fully in E.R.A. Report Ref. F/T22.*

With regard to the term "neutralizing," we have always considered it to mean purely and simply the method of protection by connecting metal frameworks to the neutral. In addition, the neutral may be connected to earth at a number of points, and this is "multiple earthing" of the neutral. Protective multiple earthing is a combination of these two features; it must be admitted that some slight confusion is liable to arise when the multiple earthing is restricted to the substation and the termination of distributors, whereas in other cases the neutral is earthed at each consumer's premises. According to "V.D.E. 0140/1932 Recommendations for Protective Measures in Installations with Working Voltages under 1 000 volts," neutralization means connection of the parts to be protected to the neutral conductor which is to be earthed in general near the substation, at least at the ends of the feeders in overhead-line networks, and also at points in the network where there are good earths such as water pipes. Connection between the frameworks and neutral must not be made on portable appliances, but a separate earth wire must be run back to the fixed part of the neutral.

With regard to the conflicting statements relating to protective multiple earthing, it should be pointed out

* *Journal I.E.E.*, 1929, **67**, p. 359.

that this system of protection does not depend on the resistivity of the earth. Almost entire reliance for protection is placed on ensuring a low-resistance metallic circuit for the fault current. There is no doubt whatever that under normal working conditions a protective multiple earthing system is much safer than one earthed in the ordinary way. It should be realized that to make a system "absolutely safe in all conceivable circumstances" represents a higher degree of protection than is ever obtained in practice.

The real object of salting is to reduce the resistivity of the soil around the *outside* of an electrode. There is thus no advantage in installing a metal container around an electrode to contain the salt and so prevent its being washed away, since, if one is prepared to make the additional excavation, the container itself might as well be the electrode, and there is obviously no point in having salted soil *inside* the electrode.

The reason for using untinned copper strip is that the tinning involves an additional cost which is probably not warranted by the additional resistance to corrosion.

Considerable thought has been given to the safety of protective multiple earthing, and for details with regard to this we would refer Mr. Sharpe to E.R.A. Report Ref. F/T122.

The information given by Mr. Forrest effectively shows the large differences of resistivity which exist in various parts of the country. The seasonal variation of resistance of tower footings is smaller than that of many electrodes, because of their large size and depth in the ground. The measurement of the earth resistance of towers by means of one or other of the methods recommended in E.R.A. Report Ref. F/T127 is not difficult to carry out in the field, and, provided field testing personnel have had a day or two of practice, they should become quite expert and expeditious in the work. In this research we have always had in mind the fact that highly trained laboratory staff would not be available for such tests, and we have endeavoured to lay down the procedure simply, and with sufficient detail to enable it to be followed by field personnel.

Mr. Melsom cites a paper by Mr. Henshaw showing that differences of voltage can occur in the same room between earthed metal-work. Presumably this is a normal example of a water pipe being at true earth and an earth electrode carrying a fault current which was not sufficiently large to blow the fuse. This seems to be a case where the importance of bonding, as referred to by Mr. Sharpe, has been overlooked.

In reply to Mr. Gilbert, crushed carbon or charcoal has, we believe, been used for many years in France in connection with earth electrodes. We have no knowledge of its resistivity, but from the corrosion point of view it is obviously preferable to coke. Unfortunately it is nothing like as easily obtained, and is considerably more expensive.

We cannot understand Mr. Gilbert's lack of confidence in theoretical conductance curves; there seems to be no obvious connection between these and the current carrying capacity of an electrode, which in any case is not such an indefinite factor as Mr. Gilbert seems to think; it used to be as indefinite as earth resistance, and thereby a convenient excuse was always at hand to account for any otherwise inexplicable happenings. As a fire of unknown origin was always put down to the electrical installation, so defective earthing was blamed for any fault. But we progress, and there is no excuse now for defective earthing.

With regard to coupled rods, we have found that the best form of coupling is a $\frac{5}{16}$-in. diameter phosphor-bronze stud screwed with a B.S.F. thread. This is sufficiently strong for all practical purposes, and remains tightly screwed after driving. One of us (E. Fawssett) has not only driven coupled rods with an electric hammer but has also withdrawn them by the same means. After this double treatment the couplings were still tight.

Unexpectedly large increases of resistance when driving long earth electrodes, even if they occurred (and they never have in our experience) could be accounted for much more simply than by the suggestion that a rod had parted at a weak joint and started off again in a new direction. We have on one occasion when driving in limestone found a rod to turn through a considerable angle out of the vertical, but fracture did not take place, and no information on our records suggests that this has ever occurred. We have known a rod with an external coupling pass through a low-resistivity layer and subsequently increase in resistance. Much has been said about the increase of resistance due to oversize couplings, but we are only aware of one direct comparison of rods with external and internal couplings. This was made in light clay soil of low resistivity and remarkable uniformity; the external coupling increased the resistance by about 25 %.

In our opinion the enclosing of the top of an electrode in an insulating tube is an excellent cure for surface gradient. If voltage gradients ever appear at a point remote from an electrode, then they can only be due to proximity of the electrode to some other metalwork. Variations in soil resistivity such as are met with in this country could not possibly account for such an occurrence.

Mr. Gilbert's statement that little improvement in the technique of earthing has taken place since he published a book on the subject 10 years ago does not correspond with the facts. This can readily be discovered by studying the literature on earthing published before the commencement of the E.R.A. researches, and is confirmed by the reception accorded to the paper by the technical Press.

The valuable and interesting evidence submitted by Mr. Shipley on the conductivity of rain-water provides confirmation of some evidence obtained on the North Wales site, where the resistivity of the soil is always high, and it had been assumed that this was due to the abnormally high rainfall in a clean atmosphere. This evidence shows clearly that a high rainfall does not necessarily mean that the soil has a low resistivity; it confirms the fairly well-known fact that it is better to install an electrode in a river bank than in the bed of the stream. The possible high resistivity of rain-water and river-water has probably not previously been realized, and it is very useful to have these data in print.

Mr. Frost suggests that further information might be included on the improvement of protective multiple earthing obtained by splitting the neutral. We have

endeavoured in this paper not to refer more than necessary to this and allied matters, since they are fully dealt with in other E.R.A. Reports.

Our thanks are due to Mr. Frost for drawing attention to an error in Table 7.* The main purpose of a tramway-system negative earth is to provide a check on rail bonding. If this is defective, current then flows back through the earth electrode and is indicated on the ammeter, which, according to the regulations, must be inserted between the negative terminal of the generator and the earth electrode.

In reply to Mr. Higgs, we are fully aware of the possibility of local action between different metals in proximity to one another when buried in soil which is not homogeneous. The corrosion experiments were so effected that this phenomenon did not vitiate the results. It has long been recognized, and has, in fact, been repeated in earthing papers *ad nauseam*, that the conductance of soil is electrolytic. The authors, and no doubt most engineers, are aware of this fact, and also that dry soil and pure water are practically insulators.

The difference between the theoretical curve and the experimental results shown in Fig. 4 is mainly due to the fact that the resistivity of the soil varied both with depth and along the length of the strips. We do not approve of the indirect jibe at theory made by Mr. Higgs, and also by other speakers. It should be sufficiently clear that until the research on earthing was undertaken by the E.R.A. the majority of this work had been carried out entirely by guesswork, which resulted in an enormous waste of material and money and often produced unsatisfactory results due to ignorance of the many factors involved. The theoretical work which has been done, both on resistance and on loading capacity, has been amply confirmed by very extensive experimental work in many different soils conducted over many years. As in many other fields, theoretical considerations alone do not provide the complete answer to an engineering problem; the best solution is found by sound theoretical knowledge backed up by "common-sense and a few tests." We are not surprised at the resistance values of two similar closely spaced rods being 30 and 60 ohms respectively. Considerable experience at driving electrodes with a sledge hammer is necessary, and without this experience one is liable to get very variable results. If an electric hammer is used this is not the case.

In reply to Mr. Purse, with large-power high-voltage installations the lead sheaths of the cables should in our view be regarded as the primary earth electrodes. To these should be bonded water pipes wherever they pass within a few feet, or where fortuitous contact is possible, and also any special additional electrodes which may be deemed necessary. The danger arising from earthing to water pipes is that small pipes may have to carry excessively large fault currents, but where there are cable sheaths in addition this is unlikely to be the case.

* Corrected for the *Journal*.

Mr. Golde's suggestion about facilitating the measurement of the earth resistance of towers by light insulation of the earth wire is very useful, and might readily be carried out.

We thank Mr. Highfield for the details he has given of the early use in this country of earth electrodes for carrying current. The voltage drop which it was found permitted the electrodes to operate continuously corresponds satisfactorily to that suggested by our own experimental work. This is a form of long-duration loading, and, as stated in the paper, the minimum voltage drop likely to cause breakdown of the electrode is 30 volts. The value of 40 to 50 volts in a different type of soil from that tested is quite reasonable.

In reply to Mr. Lovely, cable sheaths are referred to under five headings in Table 7, but possibly some additional emphasis is necessary, and this is given above in our reply to Mr. Purse. Mr. Lovely's and Mr. Sharpe's views on the use of cable sheath for earthing correspond to our own.

In reply to Mr. Raphael, we have no information on the earth resistance of water mains, although we have heard that surprisingly high values are occasionally obtained.

With regard to cable sheaths, it may be useful to give the results of tests made at a number of small substations from which cables radiated. Values which we have obtained at different times are 0·36, 0·35, 0·21, 0·07 and 0·05 ohm. At the first of these tests there was only one cable; at the last there were three. We have always assumed that low resistances were obtained with lead-covered cables because after a period of time the serving over the lead becomes saturated with moisture, and in due course may rot away entirely. Except when it is first installed it can generally be regarded as having no useful insulating value. In many soils the resistance to earth drops very quickly. A good average value for the resistance to earth of lead sheaths in an urban area is 0·2 ohm. With reference to water mains, we can give one useful value. A village water-supply consisting of about $1\frac{1}{2}$ miles of 2 in. water-main laid in sandy soil having the high resistivity value of about 4 000 ohm-cm. had a resistance of 1 ohm to the general mass of earth. The great majority of even small water systems should therefore have a lower value than this.

The only value of earth resistance with which we are satisfied is one which enables the protective operations to be carried out effectively. If we appear to have a preference for a value of 3 to 5 ohms for rural pole-mounted transformers it is because such values can usually be obtained without a great deal of difficulty, and because they provide protection for the majority of rural consumers. Undoubtedly the lower the resistance the better, but there is no such thing as a "solid earth of negligible resistance." To secure anything approaching this for a small substation in a rural area would involve a prohibitive cost; at large urban substations the same does not apply.

TELEGRAPHIC TYPESETTING

By H. H. HARRISON, M.Eng., Member.

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SUMMARY

The paper compares the somewhat similar conditions of a page-printing telegraph system and the remote control of a typesetting and type-casting machine. Differences which arise between the requirements in the two cases are explained through a brief incursion into the theory of typography, by which it is shown that the simple process of letter-counting permissible in the case of the page-printing telegraph equipment becomes one of integration of the variable body-widths of the individual type in a line of composed matter. The influence of typesetting operating requirements on the design of keyboard and receiving perforators is dealt with.

The practicability of telegraphic typesetting is shown to have resulted from the invention and application of the integrating counting indicator to a keyboard perforator whereby the operator is able to judge of the "castability" of a composed line of matter before closing the line. The remote control of the caster in the case of machines of the Monotype class is shown to be practicable, and alternative methods of effecting this are described.

A typical production scheme for a newspaper office using line-casting machines is described. Methods of inserting extra items or withdrawing such from a received perforated tape are illustrated and described. The application of teletypesetter apparatus, even where telegraphic control is not exercised, is shown to lead to an increase in operating efficiency since a higher output is reached. While the most striking advantages of such apparatus are realized in the case of newspaper installations such as that of the *Scotsman*, it is also applicable to cases where composing and casting machines are not situated in the same building. The financial results of teletypesetter operation are highly satisfactory.

INTRODUCTION

Although the possibility of setting type by telegraph had long been foreseen, until recently no practical solution to the problem was forthcoming.

The setting of a column of type is analogous to the control of a page or column printer. As compared with a receiver printing on a narrow fillet or tape, the page printer necessitates means at the keyboard for counting the number of letters and spaces which go to make up the line and sending at a suitable time a signal which will return the sheet or web of the receiving position to where the next line will start at the left-hand margin, and, at the same time, feeding the sheet up a distance equal to the spacing between successive lines of printed matter. Very much the same requirements exist in the case of telegraphic typesetting, but they are complicated for reasons which are discussed below.

There is a fundamental difference between column printing and telegraphic typesetting. In the former, the letters and spaces are of uniform width, as in the case of an ordinary typewriter. Further, the right-hand edge or margin of a column of print as furnished by a typewriter or column-printing telegraph is irregular, and successive lines of type do not take up the same width.

Thus, in Fig. 1(*a*) the sentence "Now is the time for all good men to come to the aid of the party" is shown as set up in a space of 20 units of type-face width, and the right-hand margin is irregular, as is at once apparent. Considering the first line, if the 20th unit, which is a blank, is distributed among the 4 spaces which occur between words previous to "for," the width of 20 units is exactly filled.

In Fig. 1(*b*) the distribution of the unoccupied spaces of a line over the other spaces of the same line is shown, with the result that the right-hand margin is now perfectly straight. The lines of type of Fig. 1(*b*) are said to be "justified"; and this process, which is carried out with all printed matter, marks one of the differences between ordinary typewriting, type-printing telegraphy, and typesetting.

With the typewriter there is no variation in the width of the spaces, and consequently justification can only be effected by doubling the space after any of the words in the line. Below is an example of such justification on a typewriter.

```
NOW  IS THE TIME FOR
ALL GOOD MEN TO COME
TO  THE  AID OF  THE
PARTY.   NOW IS  THE
TIME  FOR ALL   GOOD
```

It will be noticed how pronounced the spacing is in some lines. If three or more widths of space were available on the ordinary typewriter this difficulty would be largely overcome, but justification for the typewriter is not practicable since, even if the complexity of differential spacing means were adopted, each communication would have to be written twice—once to assess the amount of justification and the second time to obtain the justified text.

If the width of a line is N units (letters, figures, or spaces) and n letters plus space units were set up, then $(N - n)$ would represent the deficit to be distributed over the line. For x words in a line there are $(x - 1)$ spaces, and $(N - n)/(x - 1)$ represents the additional space required between words to justify the line.

In the case of hand typesetting, the justification is easily effected since the blanks for spacing are of different widths and can be inserted by the compositor to secure the required adjustment of the line width.

In line-casting typesetting machines, justification is automatically effected by the use of spaces or "space bands," which are expansible, and the arrangement

operates as explained diagrammatically in Fig. 2(*a*), where, for simplicity, the letters are assumed to be equal in width, which is not the case in practice. The space bands are divided into two wedge-shaped portions, so that when a justification lever is operated after a line has been composed, these are expanded from the minimum width they possess when first introduced into the

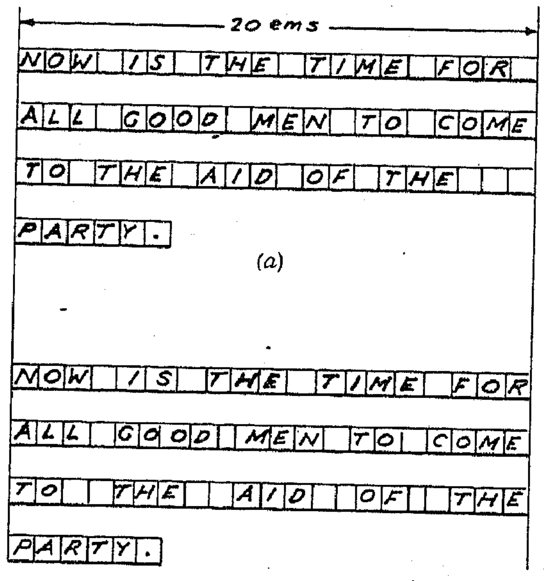

Fig. 1

line of type and spread the line until it just fills the column width decided upon [see Figs. 2(*b*) and 2(*c*)].

In typesetting machines where a line of type is built up from letters and other characters which are cast one by one, of which machines the Monotype is a leading representative, justification is effected by an adjustment of the mould in the caster, which casts the spaces of a given line so that they are of such width that the letters and spaces exactly fill the line.

Another point of difference between the column printer and the typesetting machine is that the body width of the various letters in a fount of type is not uniform. A slight digression into pure typography is necessary at this point in order that the basis of design of the keyboard counter of teletypesetting apparatus may be readily understood.

The letter "m," from which the term "em" is derived, is usually the widest letter in use and has a width equal to its depth or is a square or "quad." Other letters in the same fount have the same depth but the faces are narrower, the letter "n" usually having half the width of an "m." The pica em is the typographic unit of measurement. The area of a page of printed matter is spoken of as so many pica ems wide and so many pica ems deep. Different founts of type have different body-widths, and for the purposes of machine typesetting it is necessary to have some unit by which a comparison can be made.

In 1737 Jules Simon Fournier invented the "point" system of measurement of type bodies. The inch was divided into 12 parts and each twelfth into 6 parts, which Fournier termed "points." There are thus 72 points to an inch. For a fount of type in which the em has a width of 12 points, there would be 6 ems to the inch, or 72 to the foot. The point system was not taken up until 1872, and then only in America. Unfortunately the American 12-point pica em was based on an existing fount of type in which there are 6·0241 ems to the inch instead of the 6 which would have been obtained if a standard pica em had been developed, based on Fournier's suggestions.

The term "set size" is used to specify the width of the type body (measured linewise or "setwise") in points; and if the em quad of a fount is 6 points in width, the set size of that fount is spoken of as being "six set."

The accompanying Table gives the body width in inches and the equivalent points (American) for a certain fount of type and for the upper and lower "cases" (small letters and capitals). From this it will be seen that the same letter in the two cases differs in width, while the body widths of the characters vary among themselves.

When a typesetter of the line-casting class is remotely controlled and therefore the assembled matrices in a composed line and the integrating counter cannot be seen by the keyboard operator, it is necessary to provide at the telegraph keyboard an indicator which will show the limits at which the line is justifiable and castable.

Assuming the width of the column for which the successive lines of type are being composed is equivalent to 30 ems and referring to Fig. 3(*a*), the actual space taken up in ems at the moment considered is indicated by the pointer P_1, which moves from left to right. As shown in the drawing, 20 ems of line width has been filled by letters or characters. The space absorbed by the space bands which have been used between words in setting

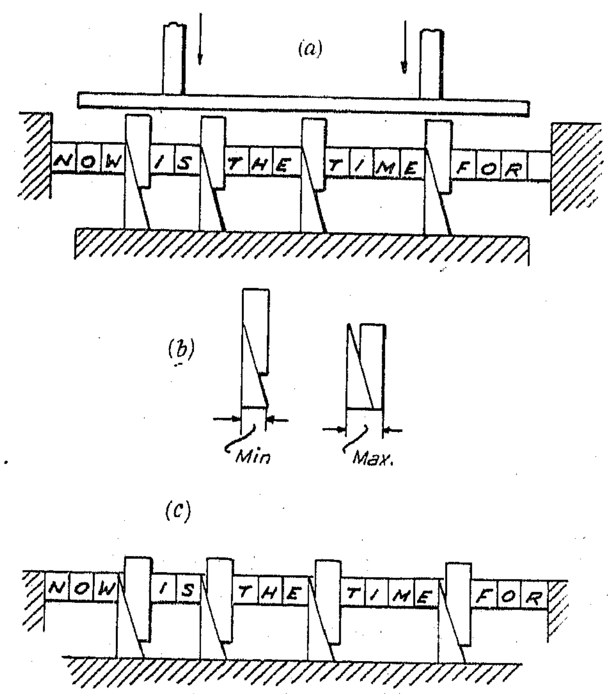

Fig. 2

up the line is represented by the distance from 0 to the pointer P_2, which moves, indicating the total minimum width of the space bands taken into use. The amount of space remaining which will allow of further letters being set up is the difference between the scale readings of P_1 and P_2 reckoned from 0. If no further space bands are set up, the setting can continue until the pointer reaches the position marked by P_2. Now P_2 shows the totalized width of the space bands without

expansion, i.e. their minimum thickness. If a third pointer P_3 is placed on the scale and moves as does P_2, proportionately to the number of space bands used in the line, but indicates the maximum width of the space bands, then the difference between the readings of P_3 and P_2 will give the total amount of justification which it is possible to effect.

This justification is carried out at the typesetting machine itself and is initiated when the keyboard operator sends the " end of line " signal, corresponding

Table

Character	Body width (in.)	Points
Lower case		
i, l	0·035	2·52
f, j, s, t, c, z	0·042	3·30
r	0·049	3·70
e	0·0525	3·79
o, v, y	0·056	4·04
a, b, g, h, n, q, u, x	0·0595	4·30
d, k, p	0·063	4·55
w	0·0805	5·83
m	0·091	6·60
1, 2, 3, 4, 5, 6, 7, 8, 9, 0	0·049	3·70
Upper case		
I	0·0525	3·79
J, S, Z	0·0665	4·80
C	0·0735	5·30
F, O, Q, T	0·0770	5·55
B, E, P	0·0805	5·83
A, P, G, L, R	0·0840	6·05
V, Y	0·0875	6·30
N, U, X	0·0910	6·60
K	0·0945	6·85
H	0·0980	7·05
M	0·1050	7·60
W	0·1120	8·12

to the " line feed, carriage return " signal in the case of a page-printing telegraph.

For any length of line represented by P_1 and for any position of P_2 and P_3, which will vary in accordance with the number of space bands in the line, the line is justifiable or castable so long as P_1 does not pass P_2 wherever this may be. This is shown by Figs. 3(*b*), 3(*c*), and 3(*d*).

Fig. 3(*b*) shows that for the position of P_1 the line is too short by the amount of the reading of P_1 minus the reading of P_3. Fig. 3(*c*) shows that the line is too long. The length of line represented by the position of P_1 plus the space bands represented by P_2 are together greater than the predetermined set width of line. Fig. 3(*d*) shows that for any position of P_1 intermediate between P_2 and P_3 the line can be justified and therefore cast, since, wherever P_1 stops, the space bands can be expanded to fill up the line exactly to the right-hand limit or margin. All that is necessary in the case of plain columnar setting is for the keyboard operator to observe the position of P_1 with respect to the positions of P_2 and P_3, and so long as P_1 is anywhere intermediate between P_3 and P_2 he can send the end-of-line signal which, at the typesetting machine, determines the final adjustment of the assembled matrices and space bands and their rejection to the casting mould.

In the case of the Monotype machine, where a line of type, as already explained, is built up letter by letter, justification is effected by casting the word spaces of a width such that words plus spaces will exactly fill the assigned length of line. This width, which varies with the number of spaces in a line, can only be determined as the composed matter is approaching the end of the line. As a consequence the words and spaces must be stored up and be inoperable until the space width can be determined. Resulting from this, the operator does not directly control the matrices as in a line-casting

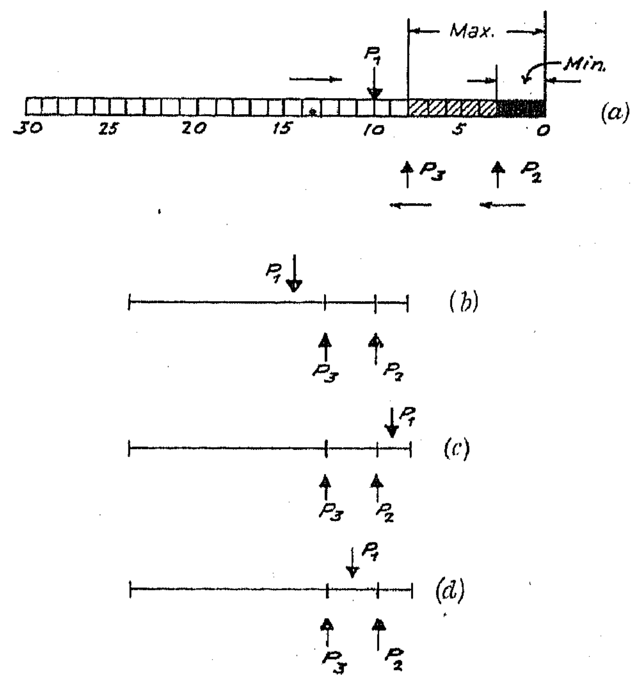

Fig. 3

machine, but prepares a perforated tape, and when he is in a position to fix the amount of justification required he punches the necessary controlling signals. This last operation ensures that the spaces, for that particular line, are cast of the necessary width to effect the required justification. Since the justification signals must set the caster before the lines of type are cast, the end of the tape must be first presented to the caster, and the individual letters and spaces are cast in the reverse order from that in which they are set up or read. The application of an indicator, which does not merely count the number of matrices and space bands but integrates their body widths, as an addition to a telegraphic keyboard has made possible in practice the setting of type in a line-casting machine over a telegraph channel.

Machines of the Monotype class already possess the keyboard perforator and the integrating indicator and, with the modifications detailed later in the paper, can be controlled telegraphically with the same facility as can the line-caster type of machine.

To control telegraphically a line-casting typesetter no alteration whatever is made to the machine ; all that is necessary is to attach a control unit, which operates the mechanism ordinarily controlled by the key levers,

and it is not necessary to remove these. The control unit is operated from the telegraph signals sent over the line.

Theoretically, at least, there is no need for the keyboard operator to be a compositor, but actually the best results can only be obtained by the employment of personnel who understand the setting of type.

In telegraphy the 5-unit code is universally employed, but if it had been possible to see ahead a little there is no doubt that a 6-unit code would have been adopted. In the early days when long-distance telegraph links were made up of long and costly aerial lines, the reduction in transmission speed caused by the adoption of a sixth unit would have been a serious matter. Now, owing to radical differences in the line plant and the extension of the transmission range, long distances are bridged by the start-stop teleprinter with a larger output and requiring a 7-unit code.

The requirements of typesetting are such that at least a 7-unit code is necessary, and this is obtained by using a 6-unit code with shift and unshift signals.

In typesetting installations it is possible to introduce case-shifting means in the control unit, but there is an alternative in which by modifications to the transmitter at the sending end and to the receiving perforator at the receiving end, shift signals are automatically inserted on change of case, normal transmission being suspended while these signals are being sent over the line. Examples of this method are described later in the paper.

(2) TELEGRAPHIC CONTROL OF LINE-CASTING MACHINES.

(a) The Cycle of Operations

In a line-casting machine, matrices of brass in which the various types are cut are selected from a magazine under the control of a manually operated keyboard and are assembled in a line. The assembled matrices form the closing side of a mould into which molten type-metal is forced by a pump, and a solid line of type is thus cast ready for printing. The matrices, after leaving the mould, are returned automatically to the magazine, each matrice being distributed to its correct channel or chute there. Each letter will have sufficient matrices in its appropriate chute to meet the usage frequency demands upon it.

Fig. 4 explains the cycle of operations. The keyboard KB releases from the magazine the successive matrices to form a line of printed matter. These matrices are delivered one by one to an assembly frame at B, and on completion of the line and after automatic justification the frame is elevated to C by the movement of a hand lever operated by the compositor. At C the line of matrices is removed from the assembly frame and is automatically taken to the casting point at D, from which the line of cast type is ejected; it is now ready for making up. The line of matrices is automatically removed from the caster, and at the point E is raised vertically, the individual matrices being distributed at F to their appropriate chutes in the magazine M. On the transfer of the line of type from the assembly frame, the compositor can commence to set up another line.

With teletypesetter equipment the assembly of the matrices with their space bands is effected by the addition of a control unit to the line-casting machine. This control unit operates the same matrix-releasing means as in manual operation, a perforated tape being used to set permutation bars in the control unit.

This process necessitates the use of a keyboard perforator to prepare the perforated tape, and Fig. 5(*a*) shows the arrangement where the keyboard perforator

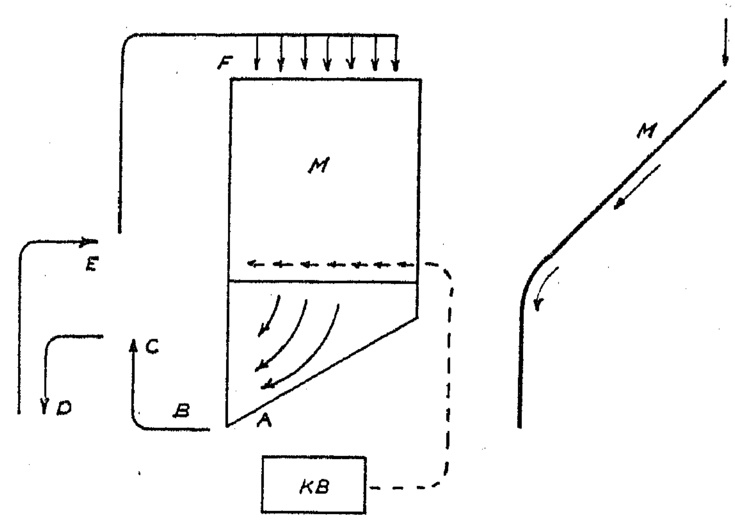

Fig. 4

is in the vicinity of the typesetting machine TSM. CU is the control unit and LCT the line of cast type, the product of the line-casting machine. Fig. 5(*b*) shows the arrangement employed when operation is effected over a telegraph line wire. KB is the keyboard perforator, and XTR a transmitter which receives the perforated tape and sends out the equivalent letter signals over the line. At the receiving end RP is a receiving perforator which produces a replica of the tape prepared on KB at the sending end of the line. This perforated tape is passed to the control unit CU, and the operation from now onwards is the same as the direct or local operation of Fig. 5(*a*).

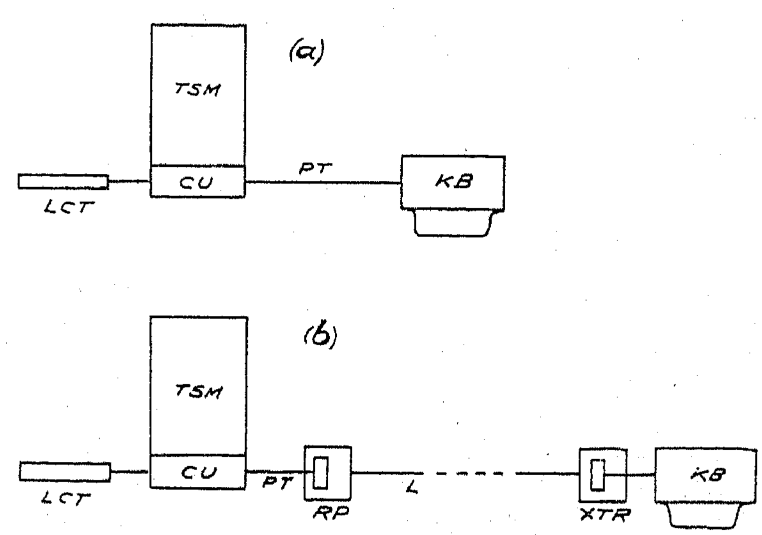

Fig. 5

Fig. 6 shows the equivalent apparatus for a Monotype machine. The keyboard perforator KB draws paper from a roll R_1 and passes it through the perforating mechanism P, where it is wound on to a second roller R_2. R_2 is then taken to the caster, where the tape is presented in the reverse order from that in which it has been perforated, as seen in Fig. 6(*b*). Obviously the telegraphic arrangements of Fig. 5(*b*) could be applied with-

out any alteration to the machine, but owing to the fact that each letter signal is represented by permutations of a 30-unit code this would not be practicable without some modification, as is explained in detail later in the paper.

The various processes which form parts of the cycle of operation of the line-casting machine are as follows :

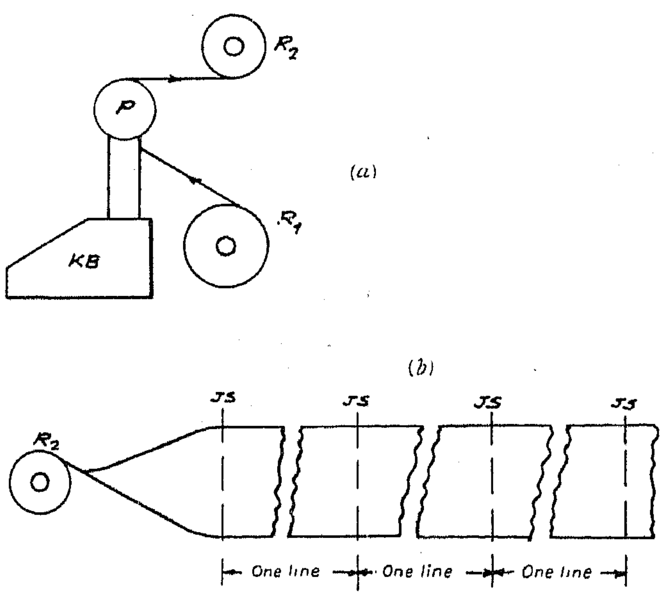

Fig. 6

(i) Release of the matrices from the magazine. (ii) Release of the space bands. (iii) Assembly of matrices and space bands in a line. (iv) Justification. (v) Elevation of assembled line and return of empty assembler in readiness for another line of composed matter. (vi) Casting. (vii) Removal of matrices from caster. (viii) Distribution of matrices to magazine. Only (i), (ii), and (v) are effected by teletype equipment, the others being automatically controlled by the line-casting machine itself.

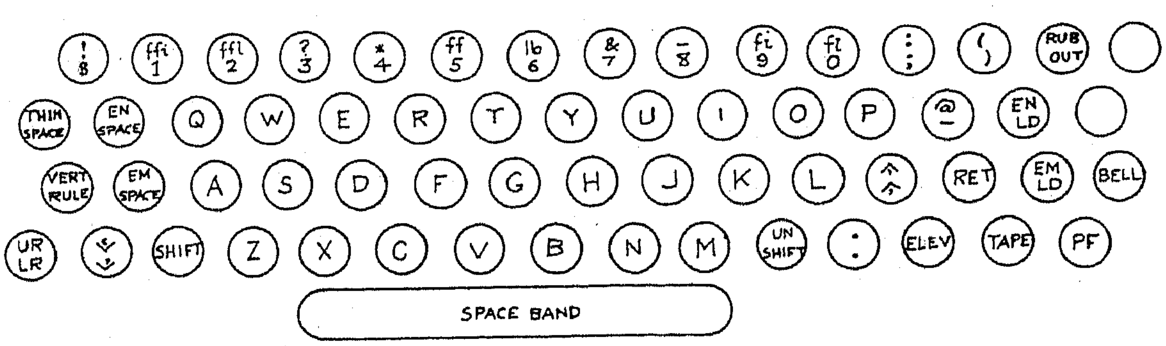

Fig. 7

(b) The Telegraph Apparatus

(i) The keyboard perforator.

Fig. 7 is a diagram of the keyboard layout. The standard arrangement of keys is used, to facilitate touch typing, and this is also the case with the keyboard employed by the Monotype Corporation for their machines. The action of the shift key is as in an ordinary typewriter, so that all characters following the shift operation will be capitals until the unshift key is depressed. Each line is ended by striking the " Return " (RET) and " Elevate " (ELEV) keys in the order named. Corrections to the perforated tape are made by back-spacing this and deleting by depressing the " Rub out " key, which causes all six holes to be punched as in standard telegraph practice. No character key is struck more than twice in succession. If the tape is perforated three times successively it is possible that only two of the characters will appear in the final printed copy. This is due to timing relationships in the typesetter. It can be got over by operating the " Tape " key, which advances the tape one step, thus interposing a blank portion of tape between the second and third repetition of the letter. This has no other effect than that of introducing a time-lag which enables the third repetition to become effective. The " Bell " key rings a bell on the receiving printer which monitors the copy at the receiving end and is used to call the receiving attendant. The " PF " or paper-feed key spaces out the paper on the platen of the printer at the end of an article.

(ii) Key-lever control of permutation bars.

Fig. 8 represents the arrangement by which each permutation bar PB is controlled by a pair of secondary bars, operated by the key levers such as KL_1 or KL_2. Each pair of secondary bars engages one of two lugs of a pair of tee levers TL_1 and TL_2 at the left-hand and right-hand extremities of the keyboard, the vertical downward branches of the tee levers controlling the permutation bar. The secondary bars are notched so that any key lever enters the notch freely without operating the secondary bar; but opposite the notch in one bar is a solid portion in the other, the bars being complementary to one another. If KL_1 is operated it has no effect on the front bar but depresses the rear bar. Key lever KL_2 operates the front bar but does not operate the rear bar. There are six such pairs of secondary bars and six permutation bars PB.

The advantages of this construction are as follows : The high and low portions of the secondary or code bars are all cut so that no two key levers can set the permutation bars in the same combination. As a result, when any key lever is depressed there will be a high portion of at least one of the two code bars which will block the path of, and prevent the depression of, any other key lever during the period in which the key lever is depressed. It is also not possible to depress simultaneously two key levers, as can be clearly seen from the drawing. The permutation bars are all positively positioned by each key, inclined cam faces which have to be accurately cut are avoided, and a wider margin of operation is attained. As the key levers only engage the horizontal edges of the high portions of each secondary or code bar

and as such edges are in line, the bars can be inexpensively manufactured and assembled. It will be noticed that a permutation bar, when set in a marking position, remains so set as long as it enters into the combination of succeeding letter signals, and is only returned to normal when it has to be rejected.

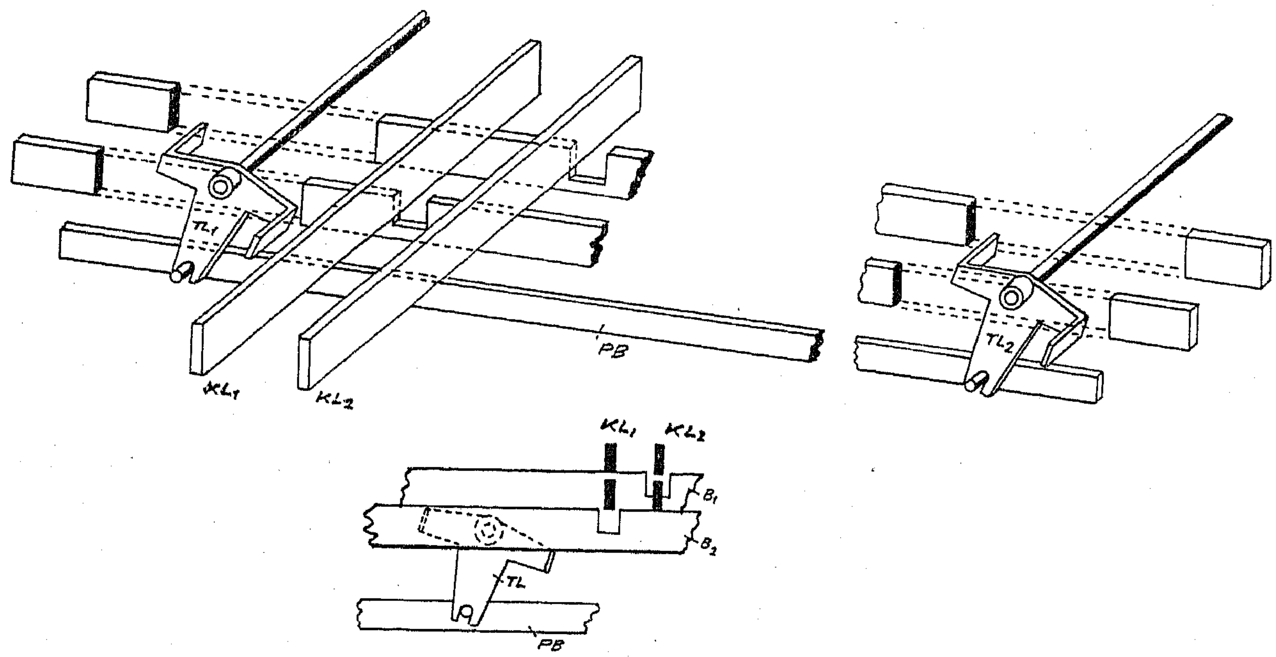

Fig. 8

When a 6-unit code, or one having a greater number of units, is employed, advantage can be taken of the fact that the total number of combinations N furnished by the code consists of $N/2$ combinations with a negative sign prefixed and the same number of combinations with a positive prefix. This simplifies matters at the receiving end since no shift mechanism is required, a sixth code bar or disc being employed which is set in one direction or the other according to the nature of the prefixed element of any given combination. The great advantage of this arrangement is that the keyboard layout of a telegraph transmitter is then identical with that of an ordinary typewriter, while in the case of teletypesetting the shift signals to change from one fount to another may be avoided.

Fig. 9 shows the method of accomplishing this where a 6-unit code is employed. SB is the shift bar, which is held in its normal position by the spiral spring. When operated it changes the sixth signal element from negative to positive, and it is arranged to be operated when certain keys are depressed and to return to normal when these are released. It can be locked in the shift position by a shift key and unlocked by release of this key. CB_1 to CB_5 are the code bars, and USB is a universal start or trip bar operated when any key lever is depressed but not operated by the shift or lock-shift levers LK, SH. The letters and figures are set up in exactly the same way as in a standard typewriter, the depression of a figure key operating the shift bar to make the necessary change in the letter signal. Thus the arrangement is equivalent to the automatic insertion of a shift signal and is effected by the apparatus and not by the operator. In the ordinary typewriter, letters and figures are in the same case, and the arrangement described takes some of the unwanted upper-case signals to enable the keyboard to be operated as a typewriter keyboard would be. In a telegraph keyboard the letter and figure shift-keys effect the spacing between words or groups of figures, but in the keyboard now described a special space signal has to be provided, so that in this respect also it is similar to a typewriter keyboard. The letters which on a typewriter are upper case, are sent out after first depressing the shift key and releasing this, as in standard operation, when the upper-case character or characters have been

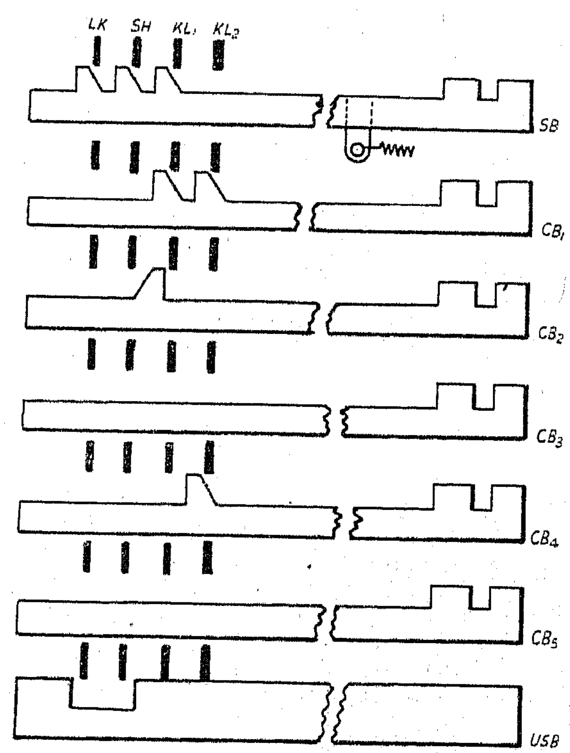

Fig. 9

set up. Actually there is no necessity for this, and the shift and lock-shift keys could be dispensed with. The keyboard would then, however, be unfamiliar to a typist.

Where shift keys are employed on a keyboard it is necessary for the operator to be certain that, before he starts transmission after a pause, the distant apparatus is in the right case. If, for example, a previous message had ended on a group of upper-case characters and the

lower-case signal had been omitted at the termination of these, the matter now transmitted would be an unintelligible jumble. The trouble could be avoided by the operator making it an invariable practice to send one or two lower-case signals before sending further matter. His attention can be drawn very simply to the necessity of

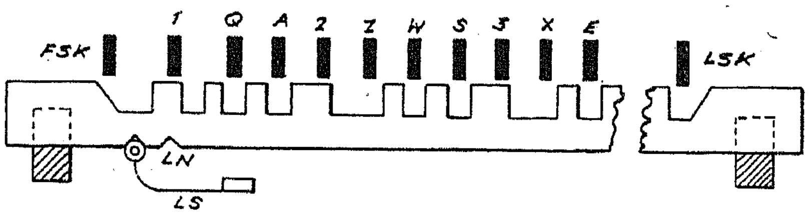

Fig. 10

restoring the apparatus to the right case by the arrangement shown in Fig. 10. When the figure shift-key is operated the notched bar is drawn to the left, in which case all lower-case keys are locked against operation. If the operator now starts up on a lower-case character he finds the keyboard locked and he must send an unshift signal (lower-case signal) before he can proceed with transmission. As soon as he sends this signal the bar is shifted to the right and frees the keyboard for lower-case operation.

(iii) The perforator mechanism.

Perforation is effected by the mechanism shown in Fig. 11. The permutation bars set from the keyboard control the operation of interposing pieces IP carried in a cradle C, which is raised at the right instant and forces the selected punches through the tape. On the up-

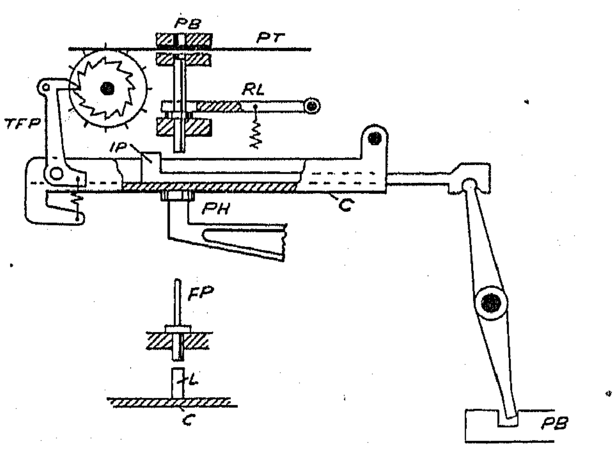

Fig. 11

ward movement of the cradle, a tape feed wheel TFP gathers in one tooth of a ratchet feed wheel and on the downward movement feeds this through one tooth. On the same shaft as the ratchet wheel is a pin feed wheel, which engages the centre line of feed holes in the perforated tape and steps this on a feed-hole space at a time. A lug L in the cradle C engages the feed punch FP and operates this each time the cradle is raised. RL is a spring-controlled comb for retracting the punches. The punch hammer PH is operated by a suitably timed cam.

It is sometimes desirable for a teletypesetting operator to be able to experiment with the setting-up of a line without perforating the tape. In addition to the space bands, fixed spaces are provided and judicious use of these will sometimes make the setting of an awkward line easier. By typing the line and taking occasional readings of the counting indicator, the operator's judgment is assisted. If such procedure resulted in perforating the tape, then, apart from the waste of tape, time would be lost in back-spacing and obliterating the line by repetition of the "rub-out" combination. This is obviated by making the punch hammer ineffective during such procedure. Fig. 12 shows the arrangement. The punch-hammer lever PHL is pivoted to a second lever L pivoted at about its middle point and which can be raised or lowered by operating the punch control lever PCL. In one position L is lowered and, carrying PHL with it, removes the roller at the right-hand extremity from the path of the lobe of the punching cam.

The teletypesetter keyboard, like the ordinary telegraph keyboard, must only operate once on depression of a key lever, no matter how long this is kept depressed.

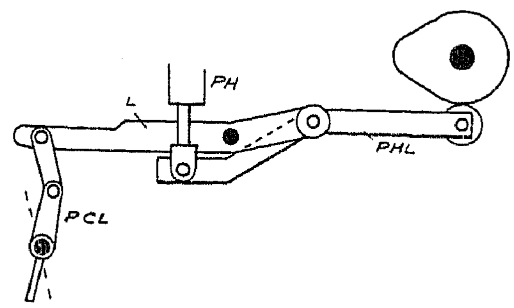

Fig. 12

There, is however, an additional requirement. If the end of a paragraph only reaches to, say, one half of the column width, then, since the mould of the line-casting machine requires for its closure a full-length line of type, the deficit must be filled with spaces. Em spaces are used, and, to obviate the necessity for repeatedly depressing the em space-key, the key is held down continuously and a release key also operated so that the punching shaft rotates until the release key is raised. This process of making a short line up to length is known as "quadding." Fig. 13 indicates the necessary arrangements.

When a key lever is depressed, the tee lever TL con-

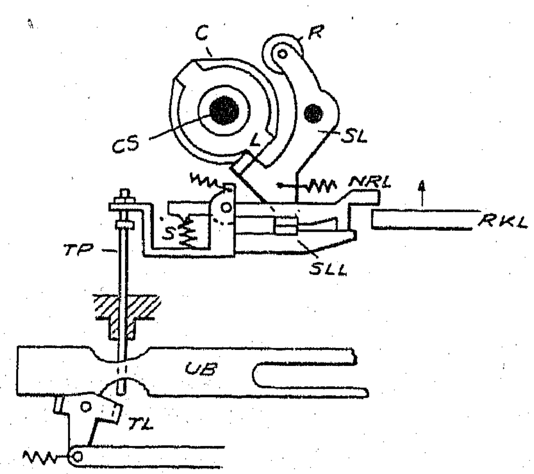

Fig. 13

trolled by the universal bar UB raises a trip pin TP which releases the stop-latch SLL from the lower (vertical) arm of the stop lever SL. Under the action of its spring, SL rotates counter-clockwise and frees the lug L on the camshaft CS, allowing the latter to start. Mounted on the same pivot as SLL is the non-repeat lever NRL, whose right-hand extremity is supported on SLL, and

by means of the compression spring S follows up the motion of SLL. As the camshaft approaches the end of its half-revolution, a cam C acting on the roller R resets SL, which, if the operated key lever has been released, is again latched by SLL. If the key has not been released, SL is latched by the non-repeat lever NRL, which, owing to its having followed up SLL, is in its lowest position with its notch in the path of the lower vertical limb of SL. When the key lever is finally released, SLL and NRL both rise and SL is held by SLL. If any character or space is to be repeated, its key lever is held down. This keeps SLL clear of SL, and if, at the same time, a release key is depressed so that RKL lifts the non-repeat lever, then the camshaft can rotate continuously and will repeatedly punch the character or space represented by the operated key-bar.

(iv) The counting mechanism.

Fig. 14 shows the two shift keys of the keyboard SK and one character key CK. Each character key-bar controls a group of permutation selector-bars to the perforator and a group of counting selector-bars CSB. A counting code-bar CB slides on a pin P on each character key-bar, and its other end is anchored to a universal shift-bar SB which occupies one of two positions according to which shift key has been operated. The counting code-bars have thus two positions, in one of which they control one or more of the bars CSB. In the other position they rearrange the counting bars CSB, and in this way the difference of body width of the upper- and lower-case characters in the upper and lower cases is taken into account. The shift-bar controls a target behind a window which indicates to the operator which case the keyboard is set for.

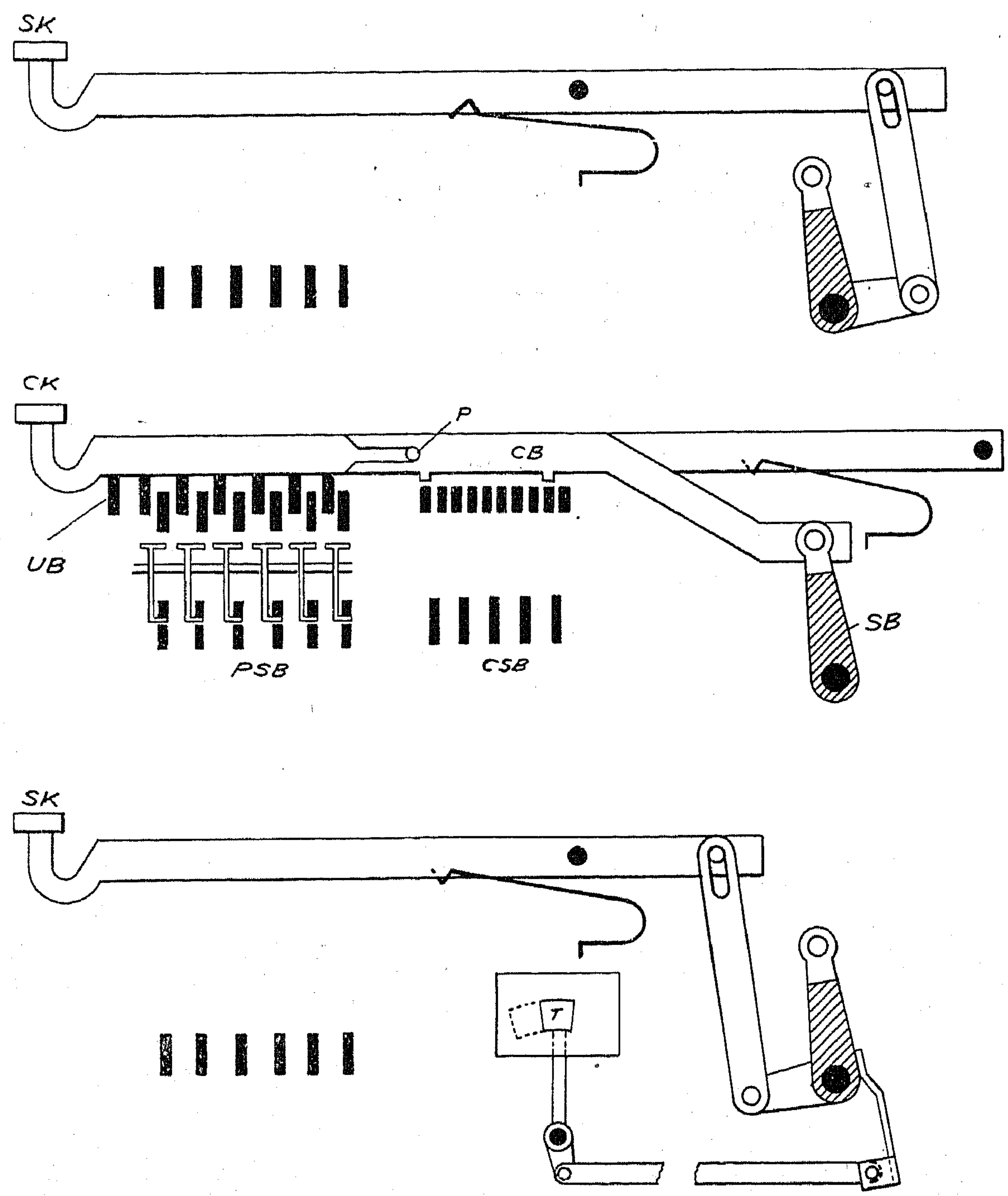

Fig. 14

Fig. 15 represents the counting indicator, which is mounted at the front of the casing enclosing the perforator and by the side of the "copy" holder. MP is the matrix pointer, which is moved each time a matrix is released by an amount representing the body width of this. In addition there are two other pointers SBP, the space-band pointers. These are mounted loosely on the same shaft as the pointer MP and are each provided with

a toothed sector. Gearing with these sectors are two gearwheels pivoted on a sectorial rack SR. The gear ratios are such that one pointer moves proportionately to the minimum and the other to the maximum possible width of a space band. Each time the space-key lever releases a space band, the driving pawl DP moves the

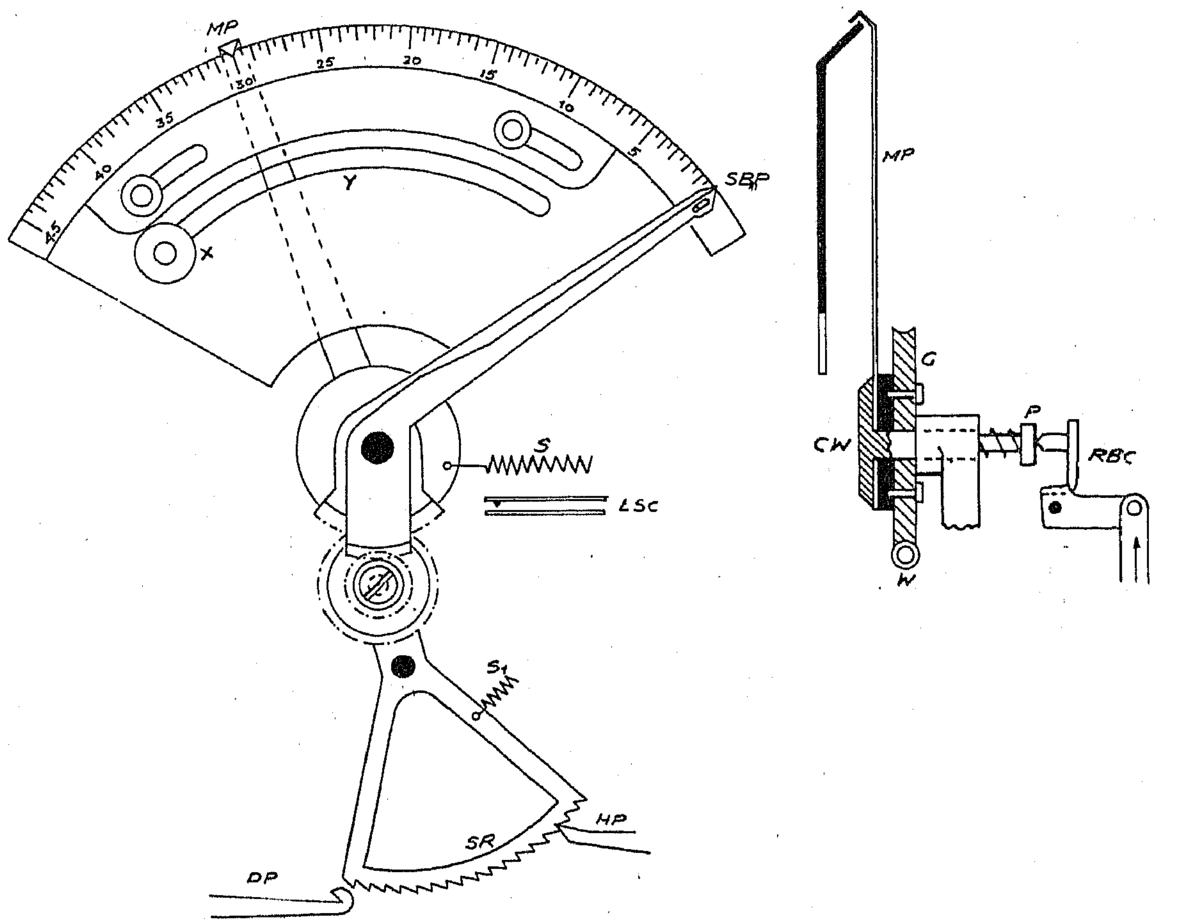

Fig. 15

rack SR through the space of one tooth. As the matrix pointer moves from its zero position, which is fixed in accordance with the required width of the column to be set and is adjusted by the movable stop X in the slot Y, it tensions a spring S which is the means for returning it to zero when a line has been closed. The space-band pointer indicating the minimum width is connected by a pin and slot to the indicating scale, which can slide in two slots from right to left. Thus the combined movements of MP and the scale indicate at any moment the remaining width of column for which matter may be set up. This arrangement corresponds to the matrix pointer indicating or counting both matrices and space bands.

The matrix pointer is driven by a gear G through a worm W and is loose on a shaft which terminates at one end in a coupling washer CW, which, by means of a spiral spring acting on a collar, presses MP against a disc of friction material and thus couples it to the gearwheel G. When the "release" key is operated, a release bell crank RBC presses on the end P, moving CW to the left and freeing MP. Under the action of the spring S, MP returns to its zero position. At the same time the pawl HP holding the rack SR is removed and SR returns to normal by the action of the spring S_1, and through its differential gears returns both space-band pointers to the zero position. Lamp signalling contacts are closed by a cam on MP as the end of a castable line is approached.

The body-width counting is effected by the arrangement indicated diagrammatically in Figs. 16 and 17.

The operation of a key lever KL (Fig. 16) shifts the counting code-bar CCB so as to oscillate a rocking frame RF having two horns at its upper end. Pivoted to an actuator bar AB is a three-armed or tee lever TL, the vertical arm of which engages in a slot in a code disc CD. The two horizontal arms of TL turn downwards, and one or the other of these engages with one or the other

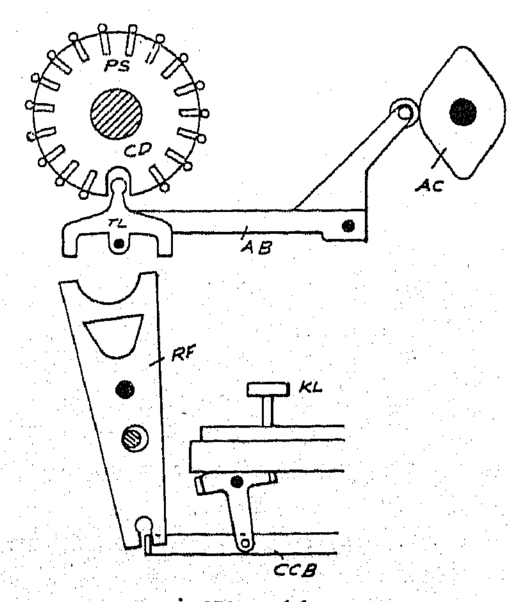

Fig. 16

of the horns of RF when the actuator bar AB is lowered by the cam AC. By means of this arrangement the code disc CD is shifted to one of two positions. There are five frames RF, five levers TL, and five code discs CD. The code discs are notched round their peripheries, and

a series of bars terminating in stops PS (Fig. 17) are arranged around the code discs. The whole arrangement constitutes a differential stop device of a type well known in telegraphy. Referring to Fig. 17, W is a worm which is coupled to an arm CA through a notch to one member of a friction clutch FC driven by a shaft DS. A gear-wheel meshing with W drives a shaft S which terminates on the worm driving the matrix pointer (Fig. 15).

A number of stop blades SB are mounted in a series of grooves in a cylinder SBC which is pinned to the shaft carrying the worm W. Their left-hand ends turn downwards over a collar C, which is free to slide along the shaft supporting it but does not turn with it. A notch N is provided in the collar at the zero position, and a bell crank opposite this notch and controlled by the bell crank ZBL and cam ZBLC pushes a stop blade forward so that it is on the path of any permutation stop PS which may have been operated. The lower end of the zero cam lever ZBL now operates the bell crank, which, turning in a clockwise direction, pushes forward to the operative position the stop blade which now stands opposite to it. While this is being effected, the reset collar C resets the previously selected stop blade by means of the cam SBRC. The stop blade which is being set in the operative position is not affected by this, since it is opposite the notch N in the collar C.

When the stop blade being reset has been moved far enough by the reset collar to clear the stop PS against which it has been resting, the counting-shaft friction clutch will rotate the stop-blade cylinder shaft until the stop blade just set encounters the newly selected stop PS. This arrangement allows degrees of movement to the shaft S to the number of 20 or more, and the distance the stop-blade shaft moves is fixed by the character selected and is indicated by the matrix pointer MP (Fig. 15), which is advanced by the rotation of the stop-blade cylinder worm W and the intervening gears.

When any function key is depressed, a stop blade and permutation stop PS is selected on the counting unit which is located next to the zero stop-blade position. When a character follows a function, the stop blade previously selected for the function will not be reset on account of the notch N but will be used again instead of the stop blade set up by the zero bell crank to determine the stopping point. Therefore the distance travelled by the cylinder SBC when a character follows a function is equivalent to the distance required for that character less the distance previously travelled for the function. Thus, function signals which should have no effect on the "castability" of a line of type are not recorded.

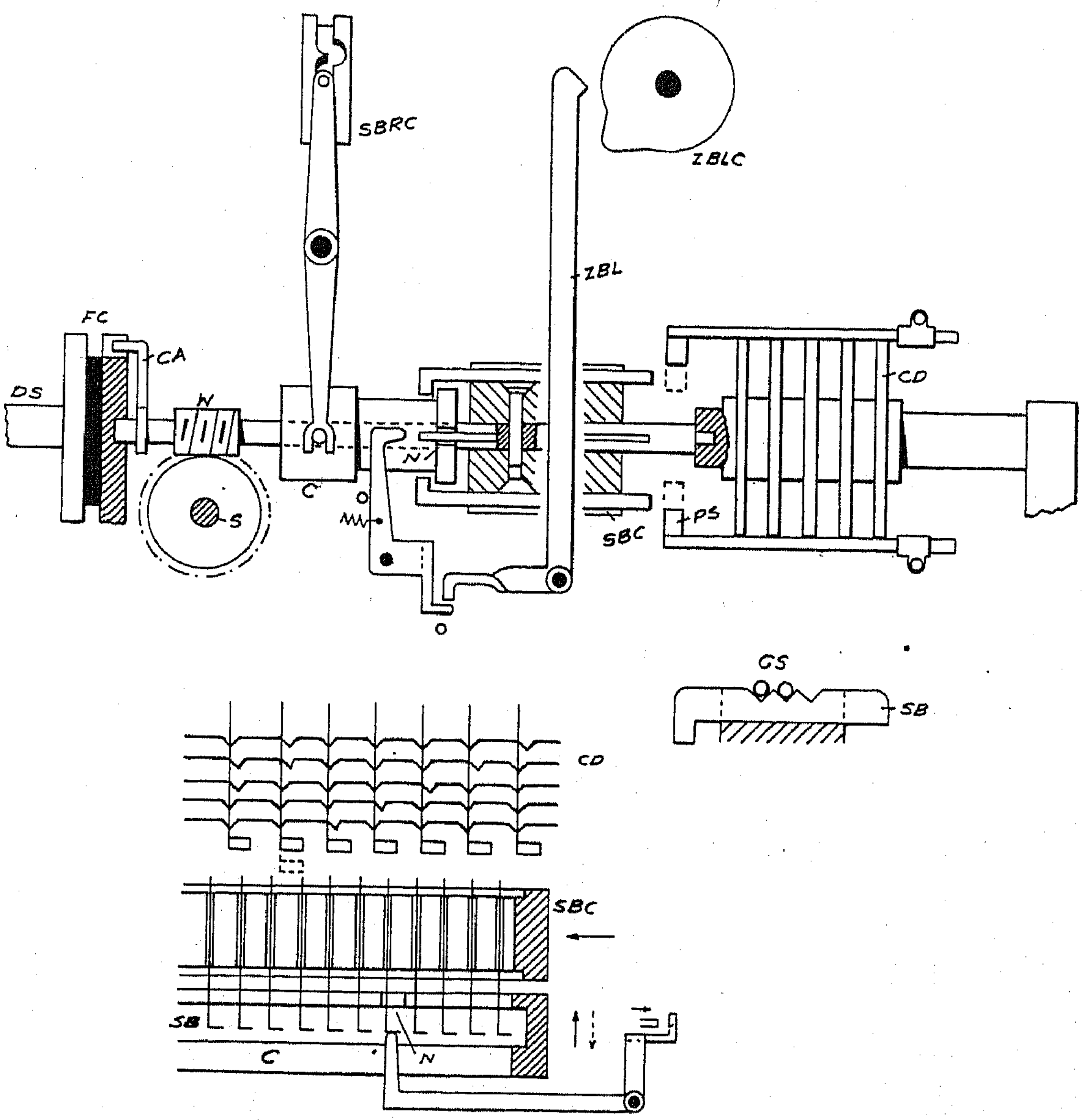

Fig. 17

(v) The transmitter.

The transmitting arrangements for teletypesetter operation are shown in Fig. 18. The distributor brush

arm rotates continuously, the start magnet SM being permanently energized so that its armature latch does not reach the path of the stop cam SC. It is driven transmitter levers have been withdrawn from the tape, and the feed pawl is moving the feed ratchet FR through one tooth and thereby the pin feed-wheel PFW.

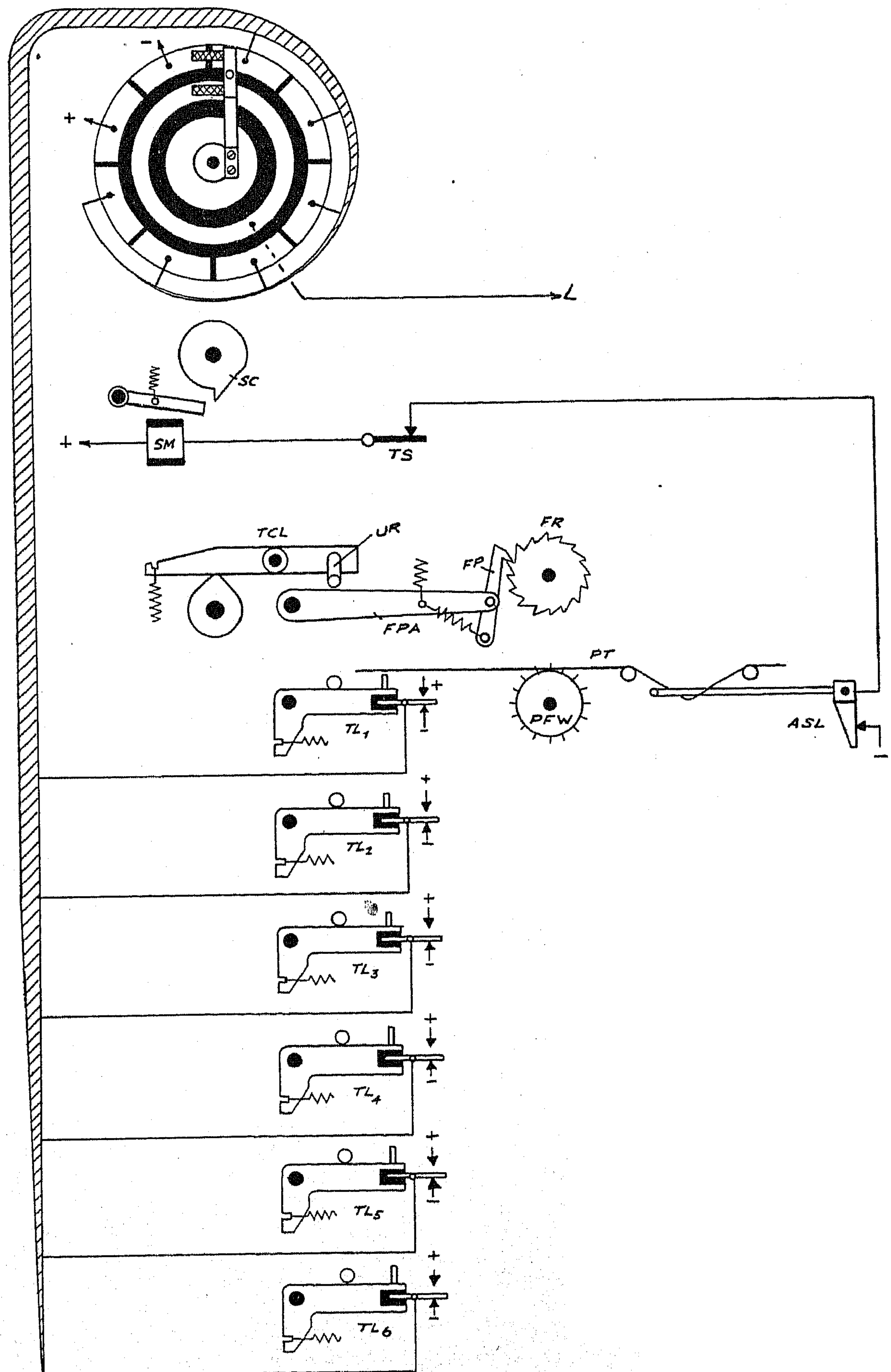

Fig. 18

through a friction clutch in the usual manner. Another cam operates a transmitter control lever, which is provided with a universal rod UR to operate the feed pawl arm FPA and the six transmitter levers TL_1 to TL_6. In the position shown the selecting pins of the six

On its passage from the perforator to the transmitter the tape passes under a pivoted automatic stop lever ASL, through which the circuit of the start magnet is taken. If the keyboard operator stops, the loop of tape shortens and finally raises ASL so that the circuit of

SM is broken and this becomes de-energized. This stops the distributor, and a stop signal is sent over the line until the tape loop lengthens in consequence of the operator resuming perforation. TS is a switch by which transmission can be stopped at any moment where this is desired. It has the same effect as ASL.

(vi) The receiving perforator.

In Fig. 19, RD is the receiving distributor, having a start segment S, six selecting segments, and a stop or resting segment R. Signals arriving over the line L operate the line relay LR, which is normally held to its marking contact *m*, as positive or marking current in the line is the normal or stop condition. The start pulse (negative) places the tongue of LR on its left-hand contact *s* and a circuit is closed for the start magnet SM which releases the brushes B_1 and B_2. The brushes make one revolution and distribute the positive and negative signal-pulses which succeed the start pulse. The positive signals only exercise a selective effect and operate one or more of the six magnets PM connected to the selecting segments of the distributor. Each magnet which is operated trips an interposing piece IP so that its left-hand end comes between the head of the punching hammer and the punches.

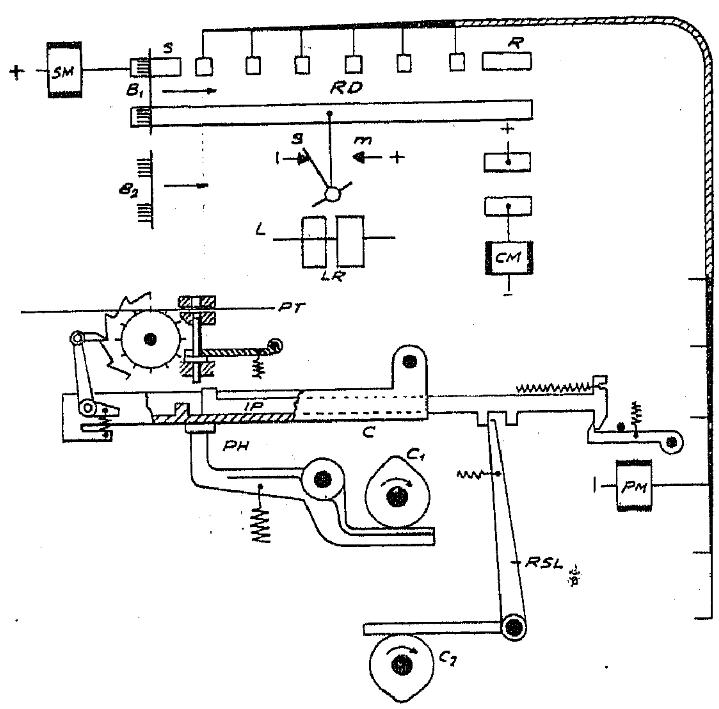

Fig. 19

Towards the end of the revolution of the distributor brushes, B_2 closes the contacts which complete the circuit of a clutch magnet CM, and a shaft carrying two cams C_1 and C_2 makes a revolution. Cam C_1 operates the punch hammer, driving the selected punches through the paper tape, and shortly afterwards C_2 operates the reset lever RSL, which withdraws the interposing pieces IP from their operative position and causes them to be re-latched by the armatures of the magnets PM. The perforator is now ready to receive the next letter signal. The same result may be accomplished by means of an electromechanical distributor of the type shown in Fig. 20.

A single magnet only is required, and this takes the form of a polarized relay PR which may be operated either directly in the line circuit or as a secondary relay controlled by the local circuit of a line relay. S is a shaft which is driven through a slipping clutch (not shown). CD is a tubular cam drum which is loose on S but is coupled to it by the tooth-and-slot arrangement seen at the left. When S rotates it carries CD with it, but the latter can also slide along the shaft to the right when required to do so. The cam drum carries six cams C distributed around and along it in spiral formation, and these have an operative and a non-operative position according as the cam drum is displaced to the right or not.

In the position shown in the drawing the cam drum and shaft S are stationary, as the stop pin SP is hard up against a fixed stop FS on the frame of the apparatus. The drum tends to move to the right initially under the influence of the spring-pressed lever SL acting on a side cam on the periphery of the "flutter cam" FC. FC has a groove which consists of a straight portion and a "go and return" portion, and there are eight of such. A two-armed "flutter lever" FL has a pin in the top of its vertical arm which engages this groove, and if FC is allowed to revolve and FL is not restrained in any way,

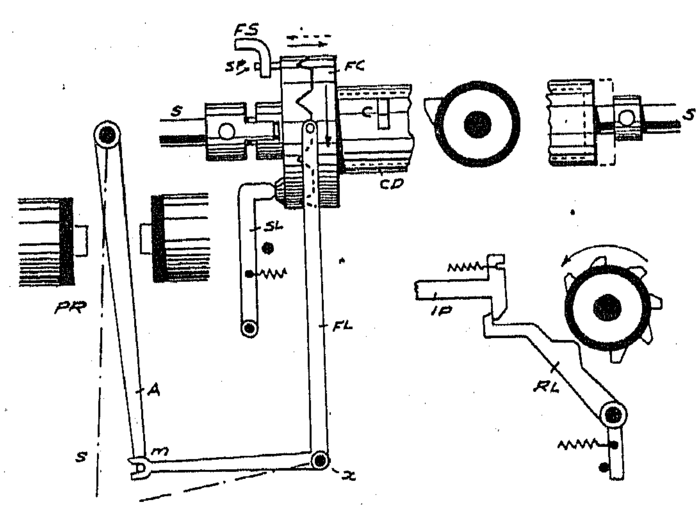

Fig. 20

the latter will oscillate to the left and then return to the mid-position shown in the drawing. This will occur eight times during the revolution of FC. If, however, the armature A is in the marking position engaging the horizontal arm of FL, and FC is allowed to make one revolution, the cam drum CD will be caused to move to the right and then back to its normal position owing to its rotation and the displacing effect of the pin and groove. Thus if the armature is in the marking position at any one of the eight periods into which the letter signal is divided, it moves CD to the operative position and selection is effected. If it is spacing, no selection is effected. When the start pulse (negative) is received, FL is freed from A and SL pushes the cam-drum assembly clear of the fixed stop FS and rotation commences. Any displacement of CD other than the initial starting one shifts the cams C into the operative position, and the one in the correct position to operate its lever RL does so, thereby unlatching the corresponding interposing piece IP.

The modern teleprinter is operated in nearly every case by some form of mechanical distributor, and this type is also employed in receiving perforators. The

receiving perforator for teletypesetting has one special feature. The tape passes in some cases directly from the re-perforator to the control unit of the typesetting machine. If there is any pause in transmission, the tape must continue to run on so that the last signal perforations are delivered without loss of time. Also, unless such provision were made to prevent it, the tape would be torn.

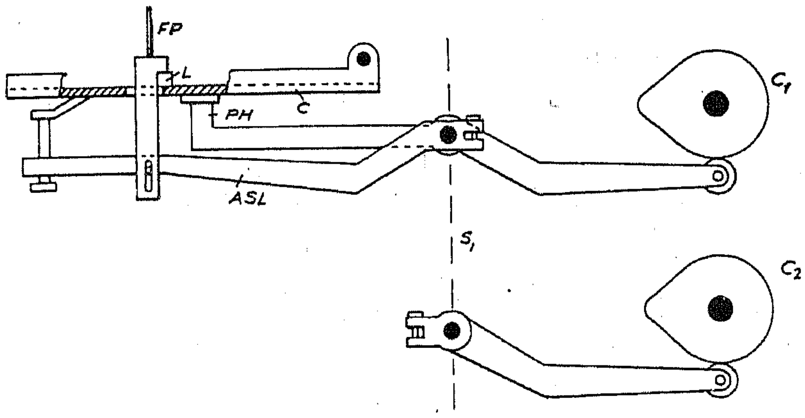

Fig. 21

In Fig. 21, C is the usual cradle supporting the interposing pieces (not shown). The punch hammer PH is loosely mounted on shaft S_1 and is controlled by cam C_1. The feed punch FP rests on a lug L on the cradle and operates as usual. It is connected by a pin and slot to an automatic spacing lever ASL which allows it to be operated in the normal manner, independently of ASL. ASL is mounted rigidly on the shaft S_1, and another lever, also rigidly fixed to S_1, is operated by a cam C_2 and will rock ASL but is without effect on the punch hammer lever PH, since this is loose on the shaft S_1, which merely serves as a support for it. With signals arriving, C_1 operates but C_2 is stationary. When signals cease, C_1 does not operate but C_2 is caused to do so after a lapse of time by the means shown in Fig. 22. C_2 is mounted on a sleeve on the shaft carrying C_1 but is normally prevented from operating by the stop cam SC and stop arm SA. A pinion P on the shaft gears with a spur wheel SW which drives a worm W. Engaging the worm is a pin mounted on the end of a trip arm TA which is pivoted to a bracket B mounted on a rock-shaft S controlled by a cam RC.

RC continually rotates as long as signals are being received, and it rocks S, thereby moving TA out of engagement with W. The worm W drives TA to the left, but each time this is released by the rocking of S it springs back to the position shown in the drawing and re-engages with W.

Fig. 23 represents a convertible shift re-perforator. It is designed for teletypesetting systems employing a

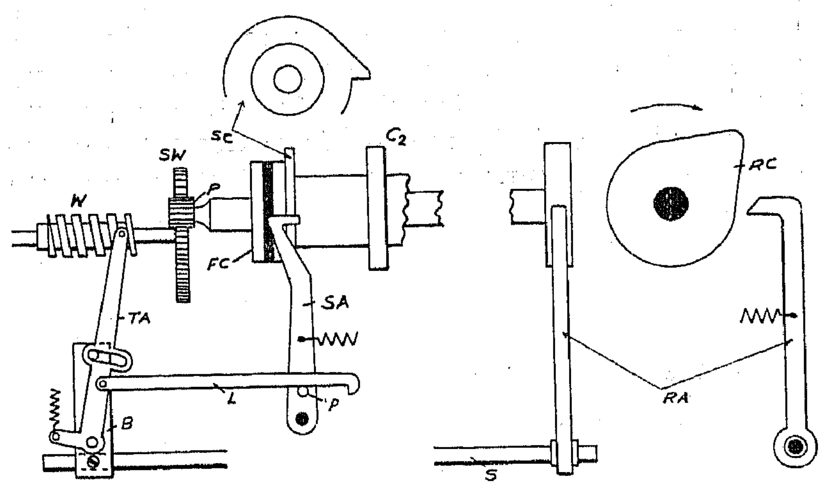

Fig. 22

7-unit code, which, by adopting shift and unshift signals, becomes a 6-unit code in the line. The punch selectors PS_1 to PS_6 are notched on their upper edges, and two shift bails B_1 and B_2 are urged against them by spring tension. One bail operates when the notches are aligned in accordance with the shift signal and the other when the unshift-signal combination is received. The bails

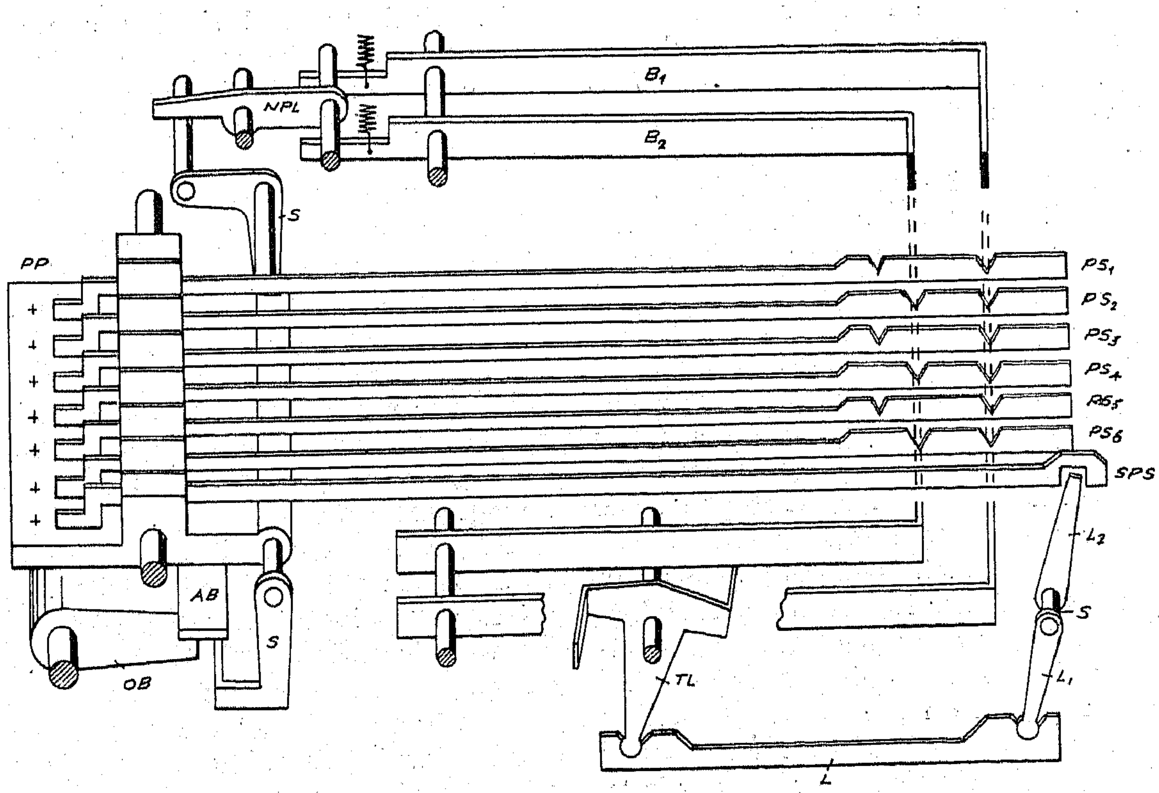

Fig. 23

control a tee lever TL to set a shift-punch selector SPS in the punching or non-punching position. TL moves SPS through link L and levers L_1 and L_2. Punching must be suspended during the shift operation. This is accomplished by the non-punch lever NPL, which rotates counter-clockwise when either shift bail is operated and moves a stirrup depending from the punch hammer out of the path of an actuator bar AB mounted on the operating bar OB. PP indicates the punching point to which the punch selectors are moved when selected.

(vii) The control unit.

Between the receiving perforator and the line-casting typesetter a translating device is interposed which takes the tape, reads it letter by letter, and sets in motion power-driven mechanism to operate a group of permutation bars. An accepted method of positioning permutation bars is directly by means of a perforated tape, and the Murray and Murray–Creed printers are examples of

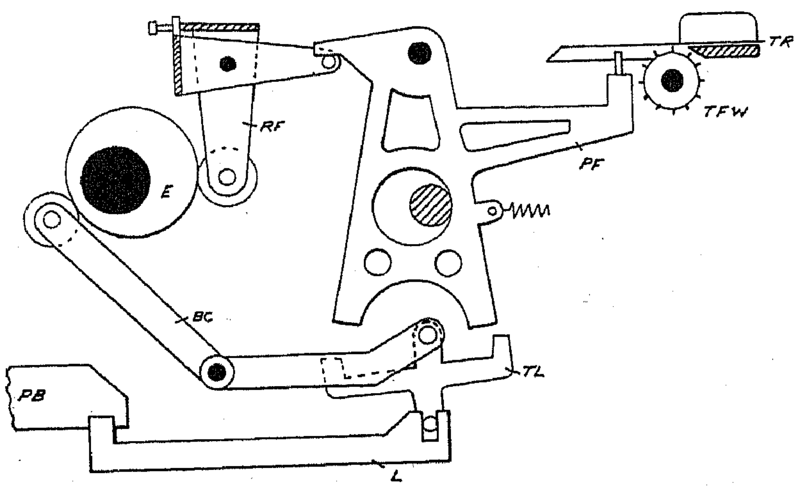

Fig. 24

such practice ; but to-day the tape is merely used as a controlling means and between it and the permutation bars a mechanical relay device is interposed. Each setting of the permutation bars selects the desired key-bar of the typesetter, and the key-bars trip the matrices from the magazine one after the other and thus set up the line for casting.

Two types of record reader designed by the Teletypesetter Corporation are illustrated by Figs. 24 and 25. In Fig. 24 the perforated tape is fed through the tape race TR letter by letter by means of the tape feed-wheel TFW. Six pecker frames PF, one only of which can be seen in the drawing, explore the tape surface when the eccentric cam E lowers the frame RF to allow the pecker frames to rotate clockwise. The pins on the upper right-hand extremities of the pecker frames are now free to enter any perforations which exist in the tape. At the lower end of the vertical portion of the frames PF are two projections, one of which is in such a position that as the eccentric E continues its motion a tee lever TL is moved or not moved, and by means of a pin-and-slot connection shifts a link L controlling a permutation bar PB. There is no reaction on the tape surface, and the permutation bars are selectively operated by power means, the tape merely indicating whether the bar is to be shifted or not. Fig. 25 is another form of record reader. The pecker levers P have a bell-cranked sword S depending from their right-hand horizontal extremity. A fork F is provided with two circular pins or rods embracing all the swords S. When the cam E_1 has released the peckers P so that they can explore the tape, the swords S are either raised or lowered, and when E_2 has advanced sufficiently the fork thrusts the swords against the prongs P_1 or P_2 of the selector levers SL and these shift the permutation bars PB accordingly. The permutation bars can also be controlled by a series of selector bars operated manually by key-bars (not shown). This has advantages in the case of teletypesetting installations, since it permits of the insertion of " flashes."

(viii) Matrix operation.

Fig. 26 shows how the matrices M are released from their vertical, sloping, chutes in the magazine by means

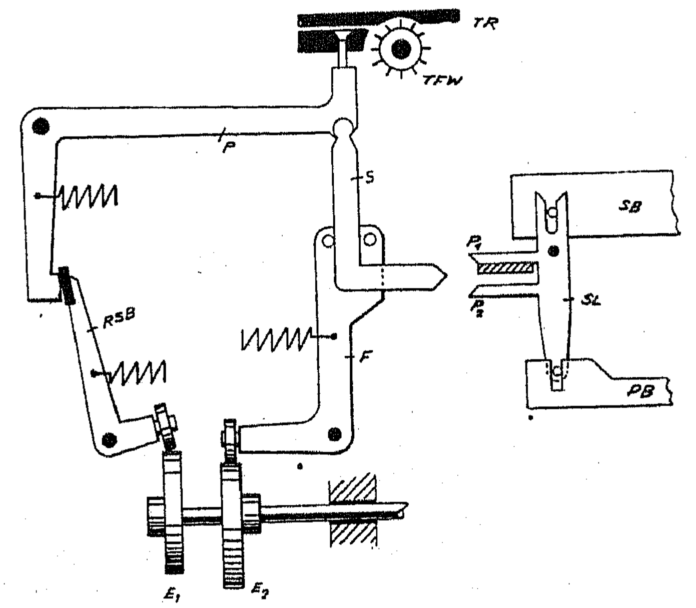

Fig. 25

of manually operated key-levers KL or automatic key-levers AKL forming part of the teletypesetter control unit. Each vertical sloping chute contains matrices having the same letter incised upon their edges, and the matrices are retained in position in the chute by an escapement E held in a groove in a semicircular supporting bar running across the whole width of the magazine. When a " reed " R is raised vertically, it pushes a lug on the escapement E upwards so that E rotates counter-clockwise. Its left-hand pallet frees the first matrix in the groove and holds the succeeding matrix fast. The first matrix leaves the magazine and, when the reed is lowered again, the escapement returns to normal, holds the second matrix in the position formerly held by the first, and allows the third matrix to fall on the second, which now occupies the exit position of the magazine.

The reed R is not directly operated by the key lever KL. When this is depressed its right-hand extremity raises a " weight " W which rotates a bell crank BC counter-clockwise. This allows a yoke Y to drop slightly so that an eccentric cam EC having a serrated portion falls on to a continuously running rubber roller RR, as a result of which EC raises the reed R gradually and more or less positively and causes it to trip the escapement E. This intermediate mechanism allows of staccato opera-

tion of the key levers while assuring certainty of operation to the reed R. It also provides a short overlap.

The lower part of Fig. 26 shows the method of operation of the above-described mechanism by means of the control unit. CB are the code bars set by the record reader. SC is a spreader cam. Above and below the bars CB are pairs of pusher bars PB_1 and PB_2. At the instant of time when the bars CB are to be set in a new combination, the spreader cam thrusts the two pusher bars away so that the setting of the bars CB is not interfered with. When the setting process has been completed, the spreader cam abruptly drops the pusher bars, which, under the tension of their springs, endeavour to enter an aligned group of notches across bars CB and the shift bar SB. Such an alignment will only occur at either the top or the bottom edges of the bars

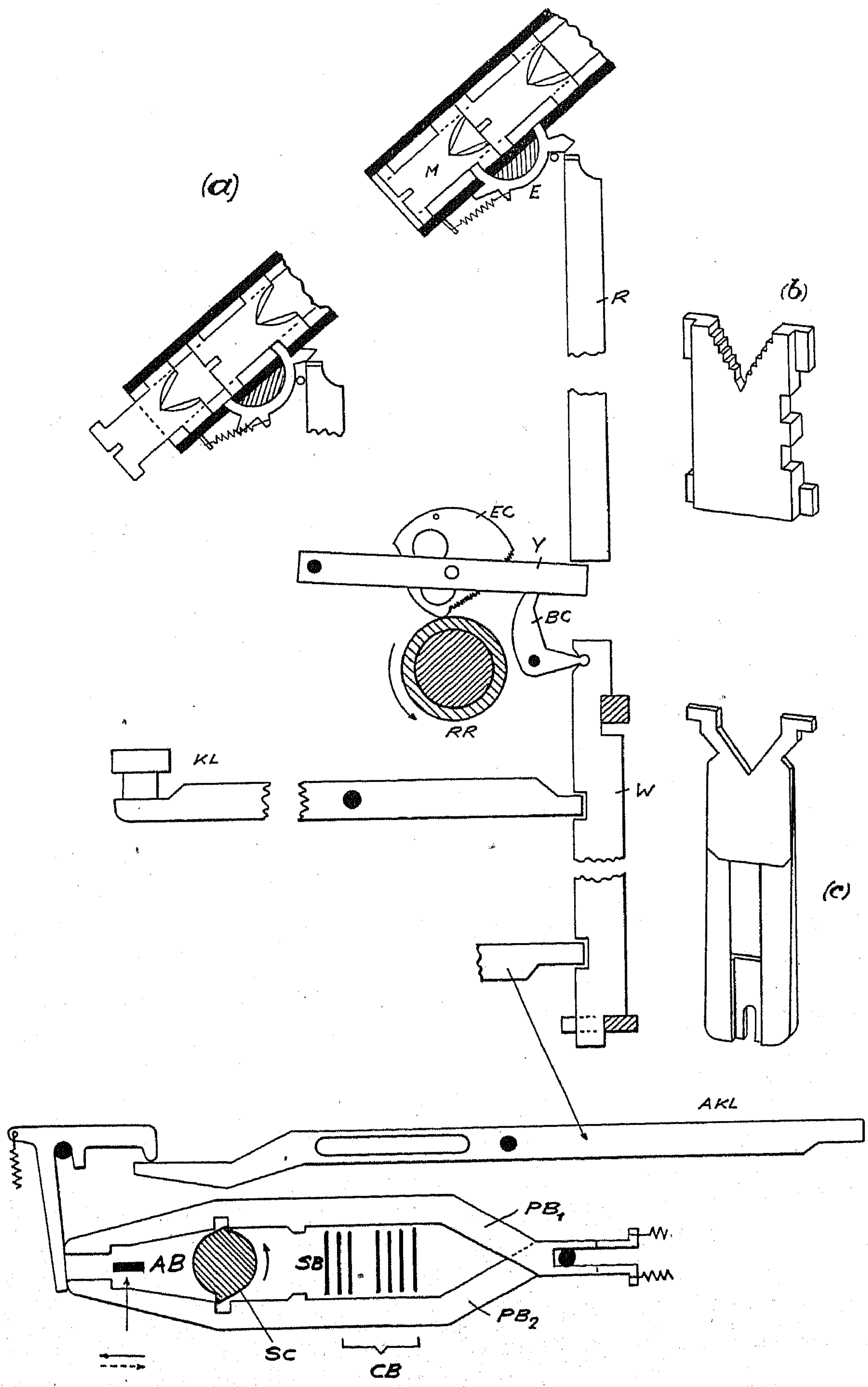

Fig. 26

CB, and therefore only one of the pusher bars will enter. When this takes place, a notch at the left-hand end of the selected pusher-bar drops over an actuator bar AB which oscillates horizontally, as shown by the arrows. The pusher-bar is carried to the left and acts on the vertical limb of an inverted L-shaped lever, rotating

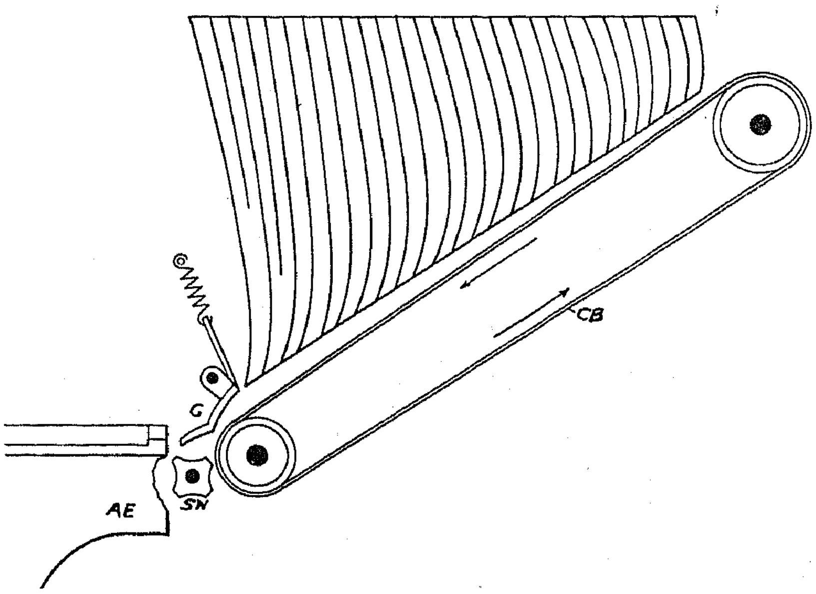

Fig. 27

this clockwise. The horizontal branch of this L lever rotates the lever AKL, which then operates the weight W in the same manner as did the key lever KL. The L-shaped lever is yieldingly suspended so that, if the escapement and controlling mechanism should have jammed, the lever will yield and no damage can result to the control unit.

Fig. 26(*b*) shows a typical matrix ; it is supported on the distribution bar by the nicked V-shaped portion, which returns the matrix to its own chute after it has been rejected from the caster. Fig. 26(*c*) shows an expansible space band.

The delivery of the released matrices and their assembly in line ready for casting is effected by the arrangement shown in Fig. 27. The chutes on the magazine lead to a series of vertical chutes which direct the matrices vertically downwards on to a continuously moving conveyor belt CB. The matrices lie flat on the belt and, arriving at the gate G, are gripped between this and the belt and deposited on the continuously rotating star wheel SW, which raises them to the vertical position and pushes them on to the assembly elevator AE. The vertical discharging chutes are variable in length. These are designed so that if t is the time taken by the matrix to fall vertically and t_1 the time for it to travel from its chute and on the belt to the star wheel SW, then $(t + t_1)$ is a constant. Thus a matrix at the extreme left-hand end of the magazine reaches the star wheel in the same time as one from the extreme right-hand end.

The control unit has six code bars and a shift bar. When the latter is in one position it prevents one group of pusher bars from being effective on any given setting of the permutation bars and allows the other group to be operated. The operation of the shift bar is determined by a shift and unshift setting of the code bars.

Referring to Fig 28, the shift bar SB is provided with a lug L by means of which it is moved from one position to the other. The vertical arm of a three-armed shift lever SL operates on one side of this lug, and a yield lever YL on the same pivot as SL presses on the other side of the lug. Assuming the shift bar to be in the unshift position, the receipt of the shift signal will cause the operation of the shift pusher-bar SPB, which rotates bell crank SBC connected by a link to a shift detent SD. The latter is moved clockwise and frees the right-hand arm of SL. SL, under the action of a spring, moves the shift bar to the left, and lug L on SB carries the yield lever to the left also. When the unshift signal is received, the pusher bar USPB moves SL counter-clockwise when it is relatched by the detent SD. YL now moves to the right under the action of the spring connecting it and the vertical limb of SL and moves the

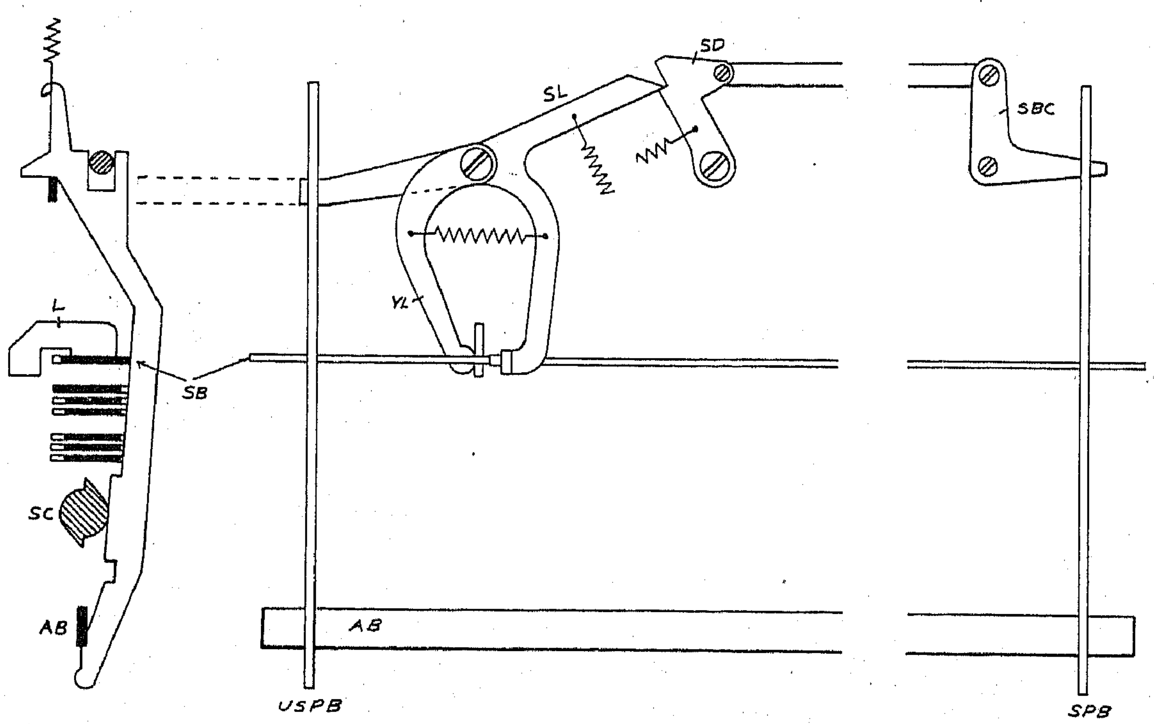

Fig. 28

shift bar to the right, thus effecting the unshift. It is usual to provide the same character twice on the casting face of a matrix—once in, say, roman and once in italic or bold face. By the use of an additional pair of shift signals, one or the other of the type faces may be arranged to be presented to the caster.

Referring to Fig. 29, it will be seen that when the matrix is in one position in the assembly elevator AE it rests on two projections or "rails" LR. A shift rail

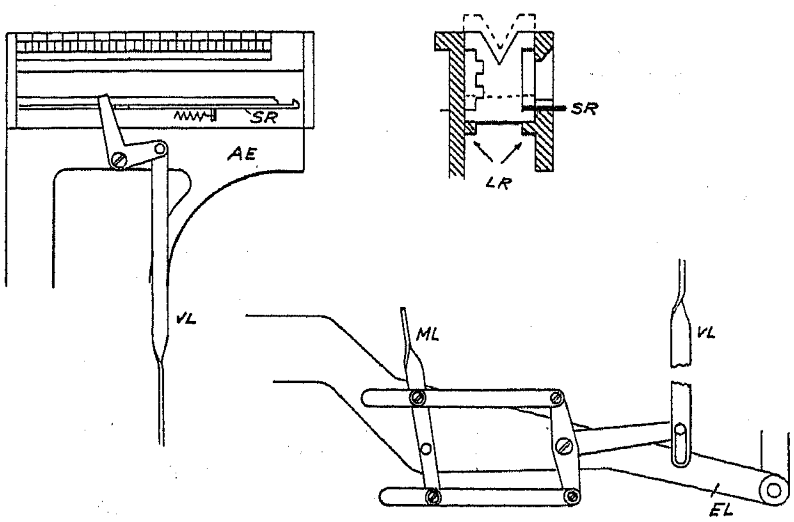

Fig. 29

SR runs across the front of the assembler block and is normally spring-held so that it is clear of the ingress end of the block. If it is shifted to the right by the bell crank and vertical lever VL, then, as matrices are presented one by one to the assembler, they mount the shift rail and assume the position shown dotted in the cross-sectional view. The shift rail may be manually operated by the lever ML through the parallel linkwork mounted on the elevator lever EL, or the two horizontal members of the linkwork can be moved to the right

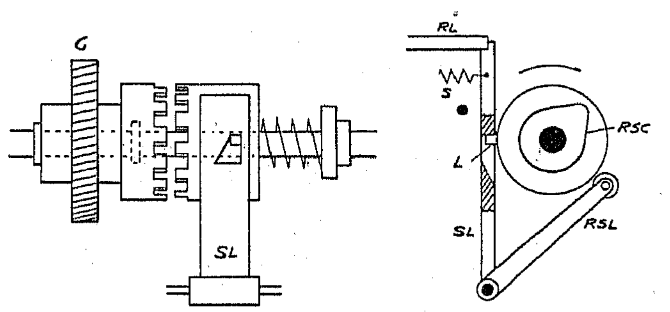

Fig. 30

(such movement of one moving the other to the left) by means of two additional shift pusher-bars.

(ix) Subsidiary operations.

Some of the functions encountered in teletypesetting require more power than their equivalent processes in printing telegraphy. Friction clutches can only be used to a limited extent, and grab clutches of a powerful type have to be employed instead. Fig. 30 shows a representative clutch in which castellated teeth are employed on account of their greater strength. The driven member is cammed out of engagement by means of the tapered slot in the stop lever SL. When the release lever RL is lifted, the stop lever SL is pulled away from the lug L and the coupling is effected. A reset cam RSC, operating on the reset lever RSL, rotates SL clockwise so that it is relatched by RL and is in readiness to cam the driven member of the clutch free of the driver.

Fig. 31 shows an arrangement where two stop levers are employed, alternately controlled by push bars PB_1 and PB_2. The shaft makes half a revolution for each release. Such an arrangement is employed to operate a shift rail or for any operation requiring a setting and resetting condition.

When a line has been composed and the assembly elevator is ready to be raised, it is necessary that the shaft controlling the record reader of the control equip-

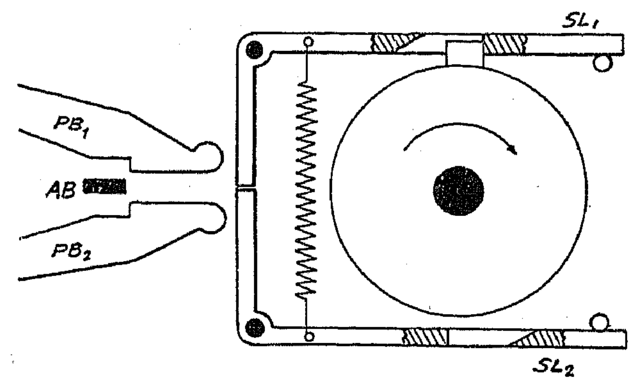

Fig. 31

ment shall be stopped. The method of accomplishing this is diagrammatically indicated in Fig. 32. When the "elevate" signal is received, the pusher bar PB rocks a bell crank BC so that the link L_1 moves to the left and the link L_2 moves to the right. The movement of L_1 moves a bell crank RBC_1 clockwise so that a stop lever SL_1, normally held in such a position that the shaft S_1 of the record reader is free to rotate, is moved to

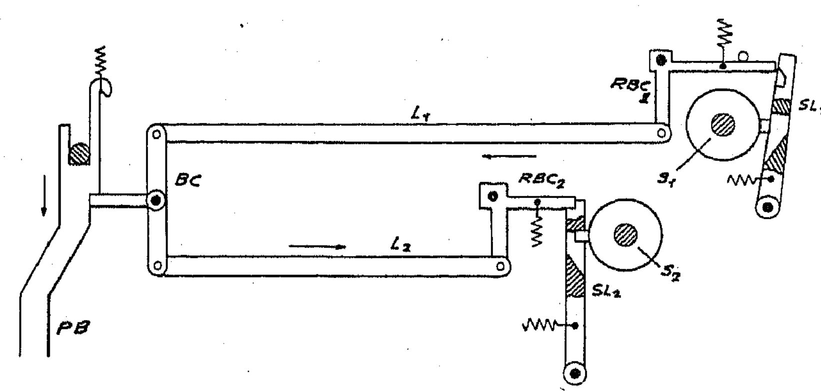

Fig. 32

the stop position and arrests S_1. Link L_2 moves RBC_2 so that SL_2 is freed and S_2 makes one revolution, raising and lowering the elevator by means of a cam (not shown).

(x) Corrections in perforated tape.

The necessity for effecting corrections in the perforated tape involves ability to read this.

Referring to Fig. 33, the right-hand and left-hand of the tape can be identified by noting the fact that the right-hand edge of the feed holes cuts through the middle of the punched signal holes. This does not, however, identify the top and bottom of the tape, which can be found by looking for the "return" (R) and "elevate" (E) signals that frequently occur. "SB" represents a

space band. If a word is to be obliterated, this is effected by back-spacing the tape the necessary number of steps and punching the rub-out signal, which is six holes for every letter to be cancelled. Corrections in teletypesetting work involve the cutting-out or insertion of several words or even sentences. The insertion of a word or words is accomplished by cutting the tape at the point where the insertion is to take place. The word or words are then punched with three sets of 6-hole perforations preceding and terminating the matter to be inserted [Fig. 33(*b*)]. The three rows of holes provide sufficient overlap for a satisfactory joint, and the 6-hole perforations give access to the last three letter signals of the first portion of the original tape and the first three signals of the second portion of this. An alternative method of making the joints is to use prepared portions of gummed paper [Fig. 33(*d*)]. The assembly of the ends of the tape for jointing is facilitated by use of the assembly block shown in Fig. 33(*c*). This is provided with a row of pins registering with the feed holes in the tape, and the ends of the tape to be joined are threaded over these pins.

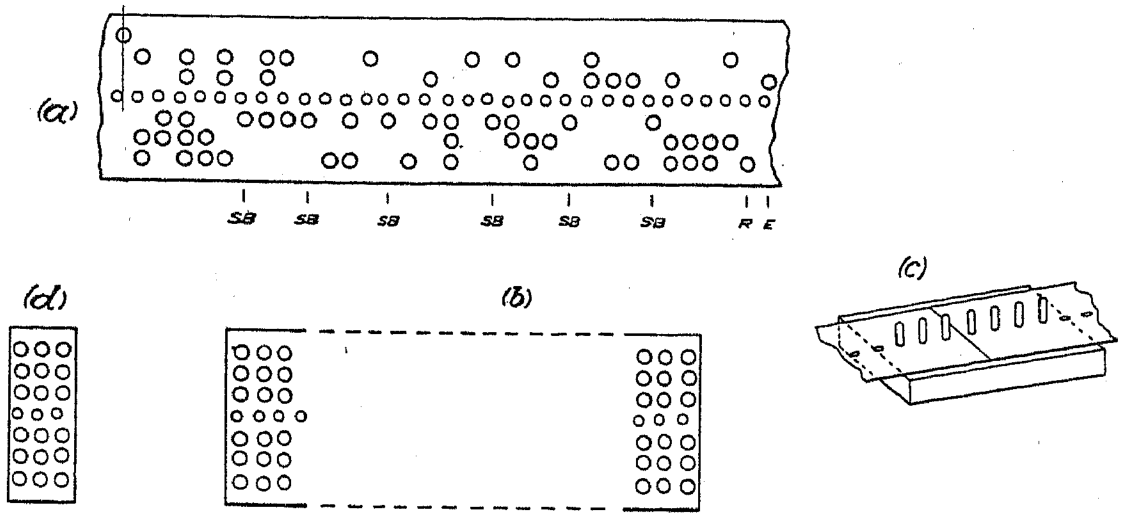

Fig. 33

Cancellation of several words may also be effected by taking the tape out of the punching head and re-inserting it at the point where cancellation is to start. By pressing the rub-out and the repeat key-levers the words or sentence will be rapidly obliterated.

(xi) Newspaper-office production plan.

A typical newspaper-office production plan is set out in Fig. 34. RE is the receiving equipment, controlled over the line from the editorial office in, say, London. This equipment consists of a teleprinter TP and a re-perforator RP, so that a roll of tape and a printed copy of the corresponding matter are furnished. These are passed to the tape-copy desk TCD, from which the printed copy goes to the proof desk PD while the tape roll is passed to the tape receiving and storage table

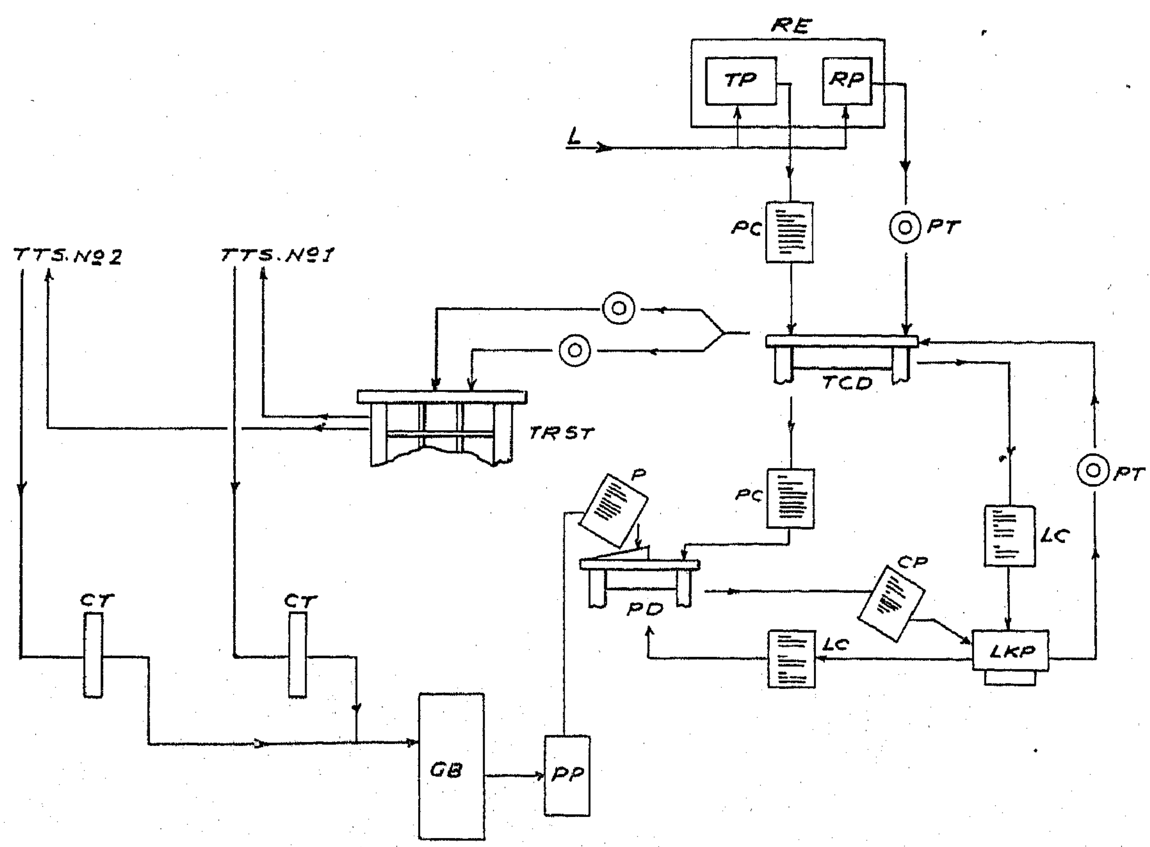

Fig. 34

TRST. From there the tape rolls are delivered to the typesetting machines TTS.

Local " copy " is distributed from TCD to the local keyboard perforator LKP, and after the matter has been perforated is sent to the proof desk PD, while the resulting perforated tape is passed to TCD; from which, over the same route as the received tape from RE, it reaches the teletypesetters TTS.

The product of the machines TTS is passed to the galley bank GB and from there to the proof press PP. The proofs furnished by PP are sent to the proof desk PD, where they are compared with the original " copy "; if any corrections are required the " copy " is passed to the local keyboard-perforator operator at LKP, who cuts out or inserts the matter added to or removed from the proof and circulates the perforated tape over the usual route to the typesetting machines.

(3) TELEGRAPHIC CONTROL OF THE MONOTYPE SETTING AND CASTING MACHINE

(a) General

The telegraphic control of a Monotype installation differs from that of a line-casting machine. This is

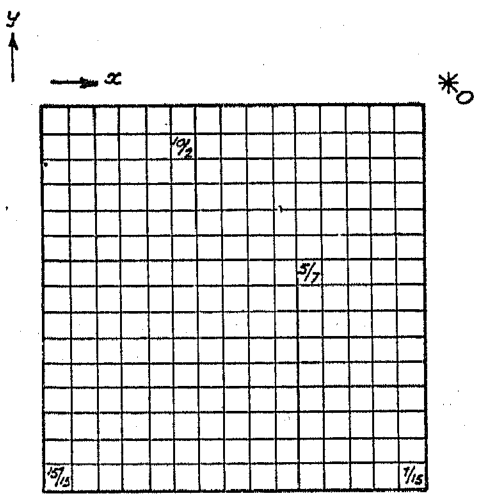

Fig. 35

due to the fact that the keyboard and the caster are separate from one another and also that the matrix selection is effected by a perforated tape made at the keyboard. The arrangement and selection of the matrices is also entirely different from that employed in line-casting machines.

The Monotype matrices are of square section and are all packed in a square matrix frame (Fig. 35) which forms part of the caster. Any one of the matrices can be brought over the casting point O in the mould by moving the matrix frame so many steps in the x-direction and so many in the y-direction. Four examples are given in the Figure, the upper number denoting the x steps and the lower the y steps to bring the desired matrix to the casting point. When this point is reached the selected matrix is pressed down on the mould to form a metal-tight joint, and molten type-metal is pumped in, thereby producing a single type corresponding to the matrix.

The cast type is ejected on to a galley, and the letters and spaces forming a line of type are thus assembled one by one in their correct order. The set-wise width of the spaces must be such that together with the characters they exactly fill the measure of the line. This width of space cannot be fixed until the composition is approaching the end of the line. Four ems from the end of the line a justification indicator comes into operation, and when composition has been completed indicates the two justification keys which must be struck in order to effect an adjustment in the caster which will ensure that all the spaces in that line are cast of such width that spaces plus characters exactly equal the desired width of line, i.e. the column width of the composed matter.

If, for example, the column width is 20 ems and the

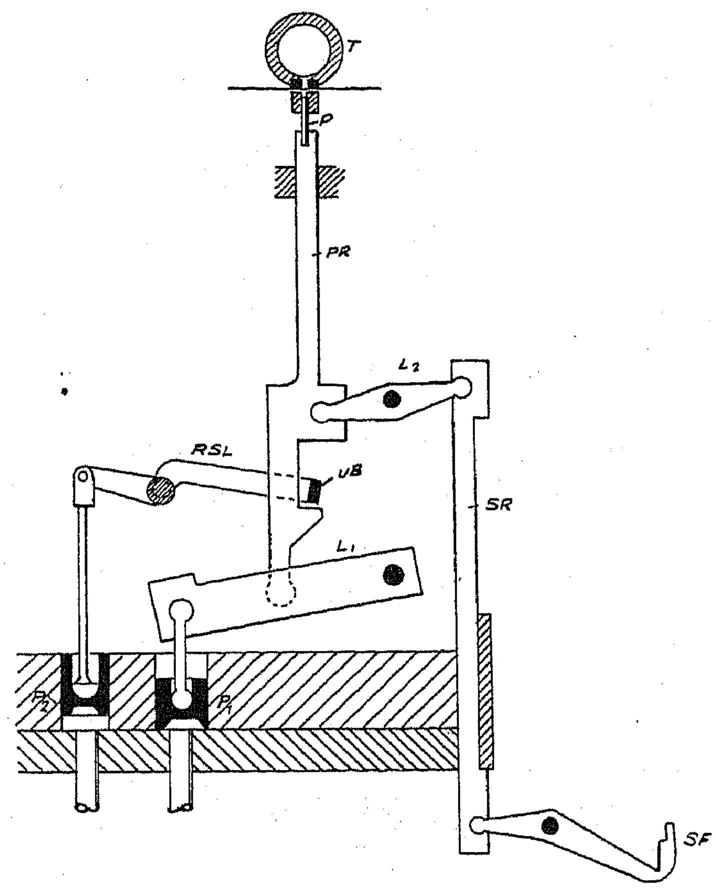

Fig. 36

composed matter of a line is 18 ems, while there are five word spaces in the line, then the necessary width for each space will be $(20-18)/5=\frac{2}{5}$ em. It is not necessary for the compositor to make this calculation, since the justification indicator does this for him; but instead of indicating the actual width of the spaces it indicates the two keys to be struck to justify the line.

(b) The Keyboard Perforator

The keyboard which effects the perforation of the paper tape is a considerable departure from the usual telegraph keyboard perforator, the keys opening valves which admit compressed air at a pressure of about 15 lb. per sq. in. to pistons which operate the punches. The essential parts of the perforator are indicated in Fig. 36. The depression of any key-lever admits air to two pistons such as P_1, of which only one is visible in the diagram. Two holes are perforated in the tape, each hole occupying one of 15 positions, so that 15×15 (= 225) combinations are obtained.

P_1, together with the other piston (not shown), lifts the two levers L_1 in a clockwise direction, thus raising the

rods PR, the upper ends of which carry punches P. As has been explained, two such punches are operated, and a paper tape is interposed between the punch and the die block mounted in a tubular container T which collects the confetti. There are 30 punch rods PR altogether, and the left-hand group of 15 determine the

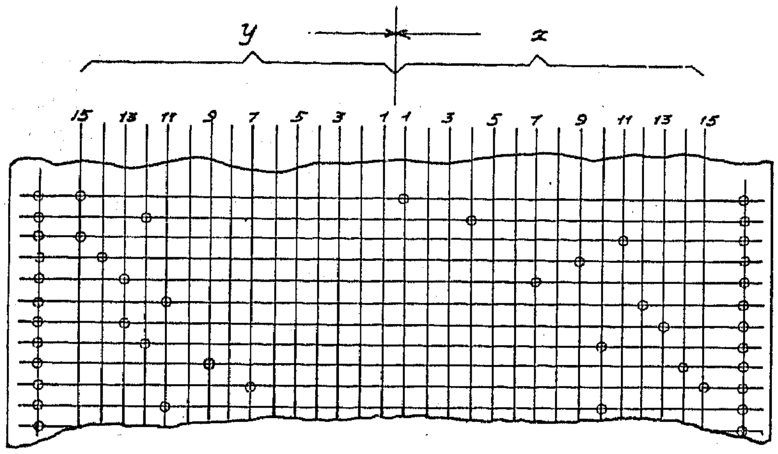

Fig. 37

movement of the matrix carrier in the y-direction while the right-hand group control it in the x-direction.

Each of the right-hand punch rods PR controls by a link L_2 and rod SR a stop finger, which is thereby brought into the path of a counting mechanism which counts up the units formed by the composed line. The stop fingers constitute a differential stop device, the stroke of the counter being regulated by them. RSL is a reset lever which retracts the punches by compressed air gaging sprocket wheels mounted at the ends of the roller forming part of the winding gear.

Fig. 38 is a diagrammatic representation of the counting mechanism. Rigidly fixed to the machine is a scale reading from 65 to 0 ems. Sliding in a groove above the scale is an em rack EMR carrying a pointer P. The rack EMR tends to move to the right, being geared to a units wheel UW which is in turn geared to a units rack UR_1, connected to two pistons P_1 and P_2 mounted in separate cylinders in line with one another. Air is continuously admitted to the right-hand cylinder to move UR_1 to the left, but with the holding pawl HP normally engaging the units wheel, UR_1 remains stationary.

Near the lower part of the units wheel UW is a units rack UR_2 sliding in a pivoted holder H; and when the holding pawl HP engages UW, the units rack UR_2 is free from engagement with UW, and vice versa. HP does not free the units wheel until UR_2 has engaged it, neither does UR_2 free the wheel until HP has engaged it; thus the wheel UW is always locked at times when it is undesirable that it should be free.

When the compositor operates a key, a universal lever on the keyboard lifts the left-hand end of the lever LL, which is linked to H, and the unit rack UR_2 is in this manner caused to engage the unit wheel UW. At the same time (by mechanism which is not shown) the holding pawl HP is raised clear of UW. One or other of the stop fingers SF is, at the same time, raised so that it comes into the path of a stop S rigidly fixed to the unit rack. Under air pressure on the piston P_1, the unit rack UR_1 moves to the left and rotates the unit

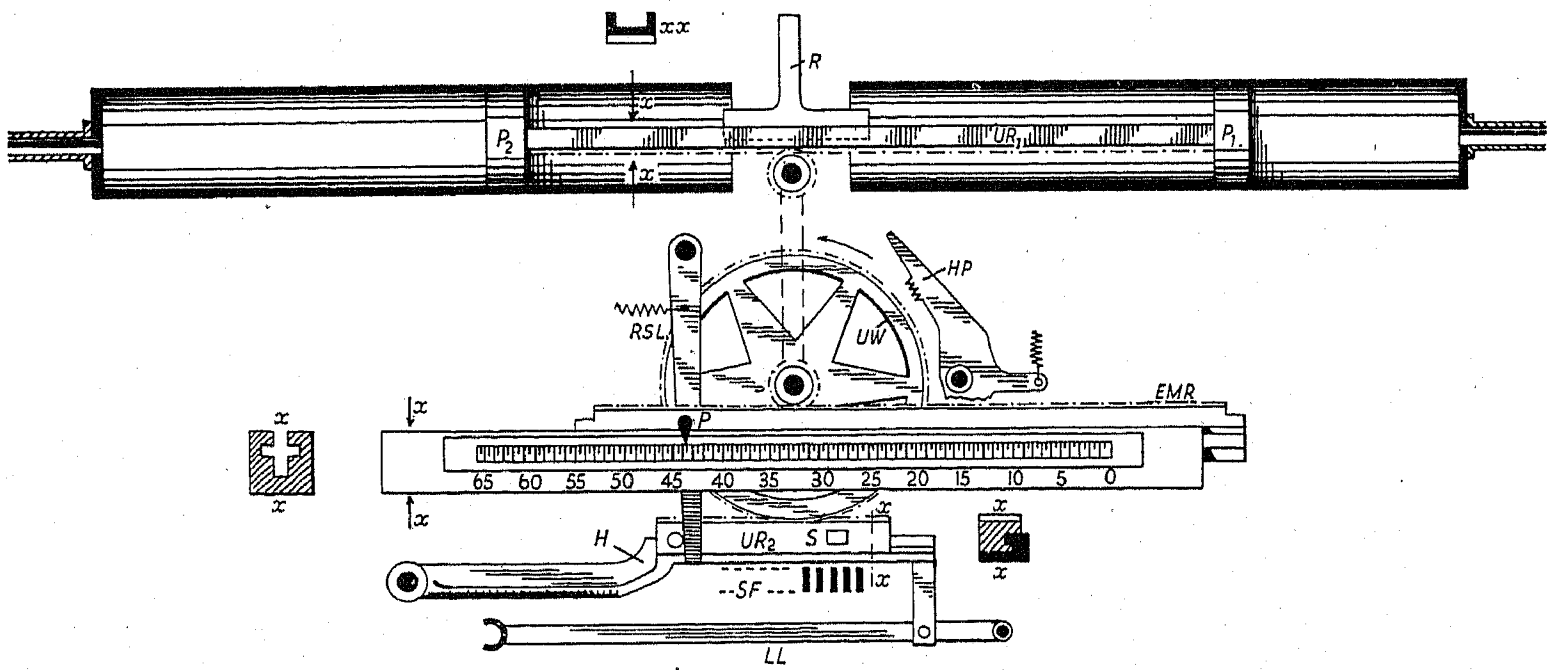

Fig. 38

constantly acting on the piston P_2 ; but the two pistons P_1, operated each time a key-lever is operated, overcome the action of P_2, which only becomes operative when a key lever is released and exhausts the air in the two cylinders in which the pistons P_1 are mounted. A further lever (not shown) on the same shaft as RSL releases the counting mechanism, as will be explained in a later diagram.

Fig. 37 represents part of the controlling punched tape. The two outer lines of holes are feed holes en- wheel counter-clockwise and the unit rack UR_2 to the right; and this motion continues until the stop S on UR_2 encounters the elevated stop finger SF corresponding to the operated key. The stop fingers SF and sliding rack UR_2 form a variable escapement and are so arranged that the movement permitted to the unit wheel is proportional to the set width of the type represented by the operated key. Such movement of the unit wheel is communicated to the em rack EMR and the pointer P is carried to the left, thus indicating

the number of ems remaining to complete the line. When the key is released by the compositor, UR_2 disengages and HP engages, so that the unit wheel is held in the position to which it has been moved. As letters and spaces

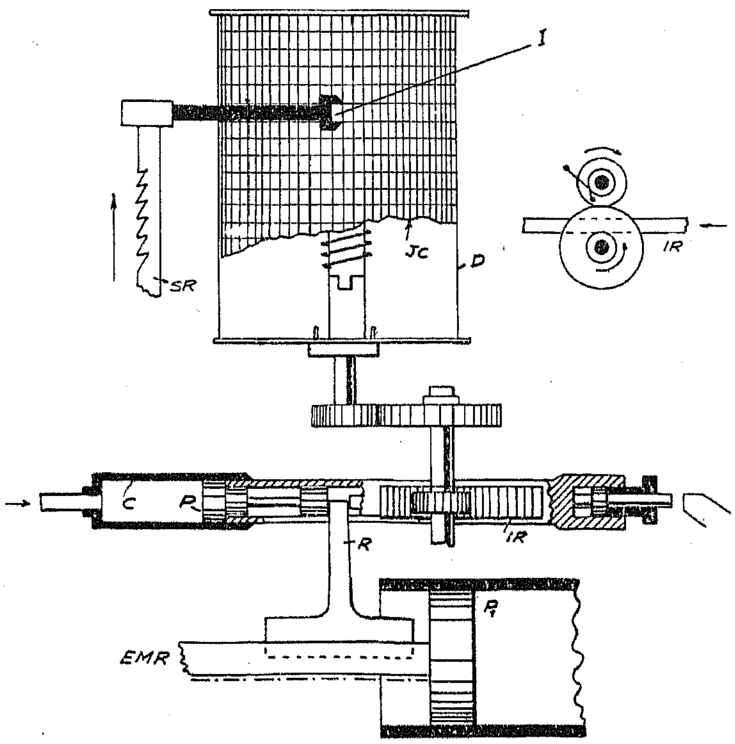

Fig. 39

are punched in the tape, P moves as described over the counting scale until it is 4 ems from 0. A bell signal warns the operator of the approach to the end of the line, and the justification indicator (Fig. 39) now comes into operation.

The justification indicator consists of a justification chart of paper wrapped round a drum D and ruled in 20 horizontal and 72 vertical divisions. Sliding loosely in the em rack EMR (as seen in Figs. 38 and 39) is a rider R, and when P_1 reaches a position 4 ems from the end of its stroke it comes into contact with R and pushes it to the left. The upper end of R enters a slot in a tube the right-hand end of which is provided with a rack IR. R is normally maintained in the position shown by the pressure of air in a cylinder C acting on a piston P; but P_1 overcomes this, and the cylinder on which R is mounted, together with P, is carried to the left, sliding in C. This allows the drum D with chart JC to rotate clockwise under the action of the spring coiled round the shaft of D. The amount of rotation will depend upon the extent of movement of P, which is controlled by whatever letters are set up after the 4-em limiting point has been reached. Opposite the chart is an index finger I which is stepped up one horizontal division for each word space occurring in the line, and this adjustment together with the final rotation of the justification drum will bring a square of the chart inside the index on which is indicated the numbers of the two justification keys to be struck to complete the line.

This detailed explanation of the counting mechanism has been necessary in order that the conditions to be met when telegraphic control is contemplated, may be readily understood. The Monotype machine is seen to have two of the primary requisites for telegraphic operation, namely (i) a keyboard perforator; and (ii) a counter for integrating the set widths of the type and enabling lines to be justified.

(c) Telegraphic Control of Monotype Machines

In the case of remote control of Monotype apparatus it is only the caster which is operated on. The keyboard is at the sending end of the line. There are two ways of applying telegraphic control to the Monotype. In one there is no interference with the keyboard which produces the standard perforated tape. Direct transmission over the line would yield a 30-unit alphabet, which at 50 bauds would mean a line speed of $16\frac{2}{3}$ words per minute only. The number of combinations required is 225, and an 8-unit alphabet would furnish 2^8-1 $(=255)$ combinations—rather more than are necessary.

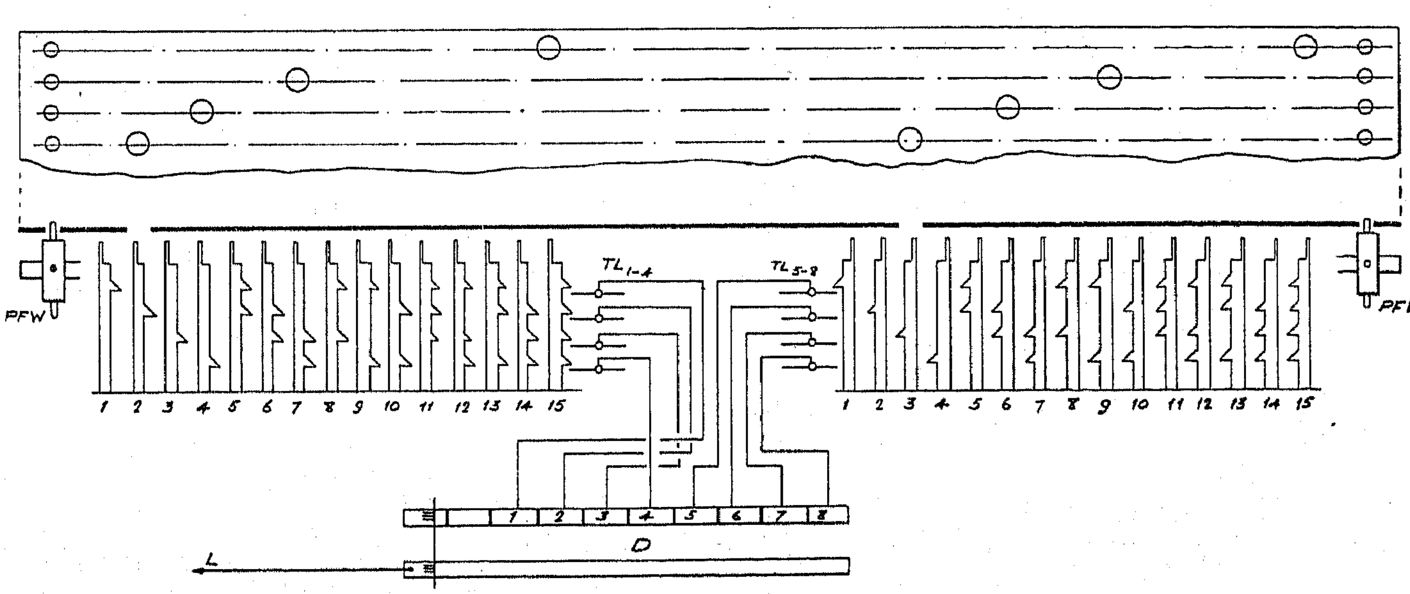

Fig. 40

To render telegraphic transmission of Monotype signals practicable all that is required is a transposer at the sending end which will take standard Monotype tape and produce an 8-unit tape, controlling the signals to line through the usual start-stop sender. At the receiving end a re-perforator would produce 8-unit tape, which, passed through a suitable transposer, would produce a replica of the original Monotype tape. This method leaves the keyboard and caster absolutely un-

changed. Such a system is shown in Figs. 40 and 41, arranged for start-stop operation.

The Monotype tape is produced in the usual manner and is then passed through a record reader which has which are connected to pivoted lifting-bars LB. PR is one of the 30 vertical rods usual to the keyboard, and each pair of such rods is provided with lugs which will raise one or more of the universal bars in the two groups

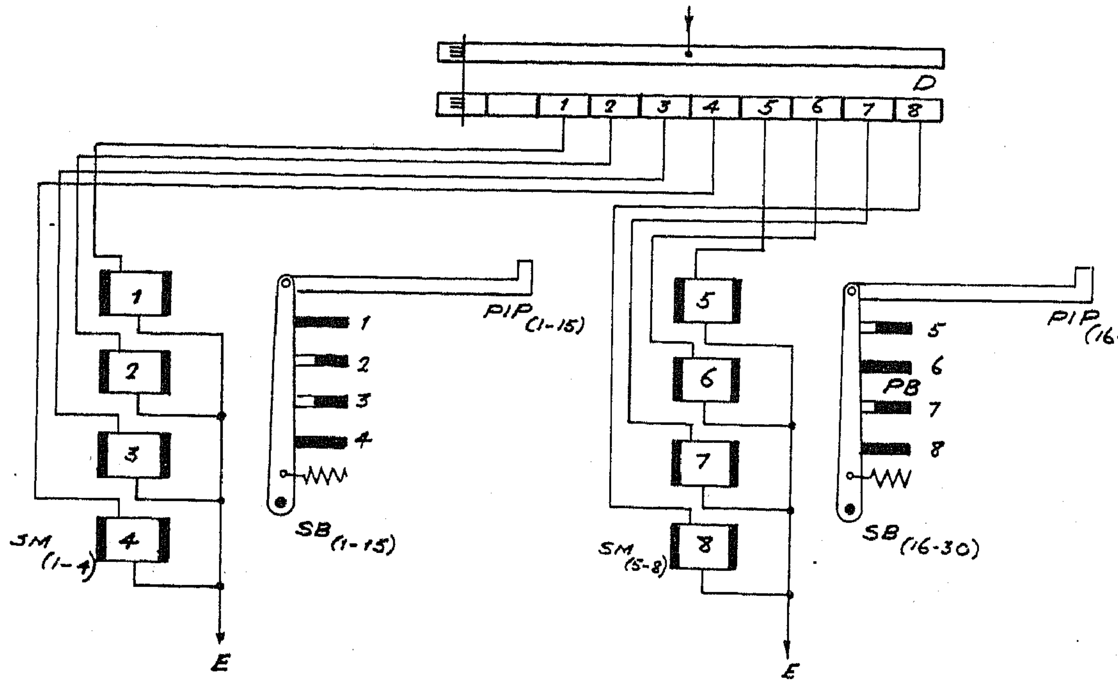

Fig. 41

two groups of 15 tape selectors each. Each of these groups variably controls four transmitting levers, $TL_{(1-4)}$ and $TL_{(5-8)}$. The tape selectors are provided with coded lugs so as to variably operate the transmitting levers. Thus the 30-unit code is transposed into an 8-unit code sent to line through the sending distributor D.

At the receiving end (Fig. 41), two groups of setting magnets $SM_{(1-4)}$ and $SM_{(5-8)}$ control two sets of code bars. Two groups of 15 punch interposing-pieces PIP are provided, and for each letter signal received one interposing piece of each group is selected and the punching effected by cam control of a cradle supporting the 30 interposing pieces. The punch block is provided with 30 punches, and the effect of the whole arrangement is to produce a replica of the original tape, which can be used to control a standard Monotype caster.

An 8-unit alphabet together with the stop and start signals amounts to 10 units. To avoid reduction in margin it would probably be advisable to run both distributors at the same speed and provide for a definite stop at the sending end between letter signals, not allowing the tape-controlled transmitter to operate continuously as shown in Fig. 18. A higher degree of precision in speed rating and control might also be found necessary. The Monotype machine does not employ shift keys, so that it is not possible to use a 7-unit alphabet in the line and an 8-unit at the sending and receiving apparatus.

The second method of telegraphic control is to modify the Monotype keyboard in such a way that it produces an 8-unit tape directly. This has been done by the Monotype Corporation themselves, who have designed the keyboard perforator of which Fig. 42 is a diagram. Two sets of four punch rods such as PR_1 and PR_2, each controlling a punch P, have lugs resting on universal bars of 4 of such bars. Those universal bars which are raised engage lugs of the punch bars such as PR_1 and PR_2 and produce the perforated signal combination corresponding to the key operated by the compositor. With this

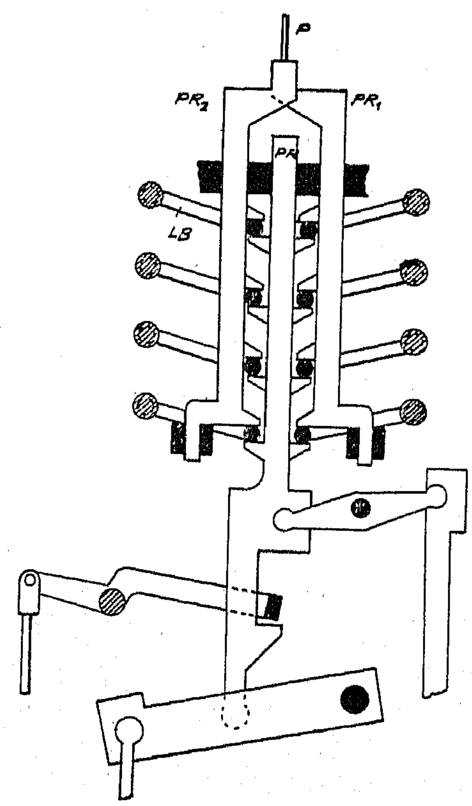

Fig. 42

arrangement there is no need for a transposer at the sending end. At the receiving end a tape transposer may be employed of the type shown in Fig. 41, but a very simple attachment can be fitted to the caster, operated by the 8-unit line signals and involving no received perforated tape.

(4) CONCLUSION

The control of line-casting machines by a perforated tape enables matrix selection to proceed at maximum line-casting speed. Pauses on the part of the compositor are not so liable to be carried over to the machine, and, as in telegraphy, the indirect control has shown itself to be superior to the direct since there is a reservoir of tape to draw on and speed irregularities on the keyboard are smoothed out. The application of touch methods of operation rendered possible by the keyboard arrangement, with their greater speed and accuracy, is a contributory cause to the higher operating efficiency when indirect control is adopted. So much is this so that even when there is no question of control over a line wire it has been found economical to operate a line-casting machine from a keyboard perforator adjacent to it.

The advantages of touch typing are also realized on the Monotype, since the keyboard follows the universal arrangement.

A comparison between a manually operated machine and a teletypesetter gave 400 000 ems per week for the latter and 234 000 ems per week for manual operation, an increased output of nearly 60 per cent, which allows ample provision for the capital cost of the additional equipment and the charges on this. Teletypesetter installations in America have shown an annual yield on the investment, after deducting operating expenses, of as much as 70 per cent.

One of the advantages of teletypesetting is that the perforated tape furnishes an easy and convenient means of storing composed matter for reprints, as type can be recast at a fraction of the cost and in much less time than that of manual resetting. To reset the type it is only necessary to re-run the tape through the control unit. There is no necessity to keep type standing, and thus savings in storage space and valuable metal are effected. This advantage is also realized by the Monotype machine, or indeed by any composing and casting machine controlled by a perforated tape. Any tape-controlled apparatus can be employed with advantage in general printing work, thereby reducing production and reprinting costs.

In newspaper work, time is the important factor. An important provincial newspaper with an editorial office in London formerly telegraphed its " copy " to the publishing office, which then had to set up the matter for subsequent printing. Now the telegraphing and composing processes have become one, with a consequent saving in time. The *Scotsman*, working between London and Edinburgh, possesses what is at present the largest teletypesetter installation in the world. The bulk of the " copy " is now cast by 9.0 p.m., using 9 teletypesetter-equipped machines. Formerly, under manual operating conditions, this process was not finished until midnight. The *Glasgow Herald* has installed teletypesetter equipment for remote-control operation between London and Glasgow.

Teletypesetting has made considerable headway in America, and its prospects in Europe were beginning to look promising before the outbreak of war.

(5) ACKNOWLEDGMENTS

The author has to acknowledge his indebtedness to Mr. A. E. Thompson, of Creed and Co., for the opportunity to study teletypesetter apparatus in operation. Thanks are also due to Mr. F. W. Humphrey, of Intertype, Ltd., for information lavishly supplied in regard to line-casting machines. Mr. G. Westover, of the Monotype Corporation, has supplied the author with a great deal of information, and enabled him to study the Monotype machines at first hand. Finally, Mr. W. P. Morris, of the *Scotsman*, has allowed the author to observe the operation of teletypesetter equipment in an important and busy newspaper office.

DISCUSSION BEFORE THE INSTITUTION, 8TH FEBRUARY, 1940

Mr. W. P. Morris: Telegraphic typesetting is and always must be to the newspaper world a matter of great importance. On normal nights we transmit over our own private wire some 50 columns of the *Scotsman*, or about 100 000 words—a fairly heavy traffic. If this traffic had to be dealt with by ordinary telegraphic methods the telegraphists would have to spell out every one of those 100 000 words on their keyboards in London, and then at the other end the compositors would have to spell them all out again. It is obvious that a system which cuts out one of these processes will be a very important economy in both time and money.

When we investigated telegraphic typesetting it was the time factor with which we were concerned. It was necessary either to provide a much greater number of composing machines and compositors—a costly matter —or else to find some other method of rapid setting. Two of us went over to the United States and discovered in the telegraphic-typesetting process the perfect answer to the problem. As an example of the saving due to telegraphic typesetting, I will give the broad outlines of a job which we have to do every night, namely the setting of the official list of business done on the Stock Exchange; this usually occupies a full page of the *Scotsman*. Before telegraphic typesetting was adopted we had to allocate 10 to 14 line-casting machines to this job after the " copy " had been telegraphed, and we never finished it before midnight. We found that we were steadily getting later and later with it, and we therefore had to do something to speed up the work. To-day we never put more than 5 machines on to this job, and it is always finished by 9 p.m.

Since we installed telegraphic typesetting at least 90 per cent of our normal traffic has been prepared for telegraphic typesetting. It may be asked why all of it is not dealt with in that way: the main reason is editorial difficulties.

The keyboard in our London office is handled by telegraphists, and after a very short training in printing style and house style they make very fine telegraphic-typesetting operators. They are in my opinion quicker and cleaner than the average compositor. We also use telegraphic typesetting locally, in Edinburgh. The keyboard works direct to the line-casting machine, and we set our weekly paper almost entirely in that way. In Edinburgh the keyboard is handled by compositors,

and though their performance is satisfactory they are not so quick as telegraphists.

In the *Scotsman* office there are both Linotype machines and machines of another sort equipped for telegraphic typesetting; the two are equally satisfactory.

Teletypesetting apparatus works quite well on any circuit on which a teleprinter can be operated. At the *Scotsman* office we operate 6 channels of teletypesetting on a 4-line circuit, which also simultaneously carries pictures or speech.

Mr. F. E. Nancarrow: The most striking feature of this paper to a telegraph engineer is that it does not mention any problem associated with the transmission of the signals sent out by the telegraphic-typesetting apparatus. The reason for the omission is probably that with the arrangements which have been provided in this country there is no difficulty in transmitting, to any part of the land, interrupted direct current such as is set up by telegraphic-typesetting apparatus or by teleprinter, so long as a single operative character occupies not less than 1/75 sec. It is just as easy to transmit from one end of the country to the other as it is to transmit over a comparatively short distance; this is due to the fact that at discrete points throughout the country there are installed sets of voice-frequency telegraph terminal apparatus which translate the d.c. interruptions into corresponding interruptions of alternating current. Up to 18 of such alternating currents can be simultaneously transmitted along one telephone line, and along the route they are dealt with in exactly the same way as the currents associated with telephone transmission.

I should like to draw the author's attention to certain of his statements referring to teleprinters. In the Introduction he remarks that some arrangement has to be made at the keyboard of the teleprinter for counting the number of letters and spaces which go to make up the line. That statement may be misleading, because in all the column-type teleprinters in use in this country, or at any rate all those which are supplied by the Post Office (and they are the vast majority), there is no such arrangement. On all these teleprinters, as the teleprinter is operated so a local record is made on the receiving portion, and the operator is made aware of the end of the line by the tinkling of a bell, in exactly the same way as with an ordinary typewriter. Where the counting of the characters in a line is necessary is in the particular case where a tape machine works to a page machine. The tape machine then incorporates a means of counting the number of characters sent and warning the operator when she has to depress the carriage-return and line-feed keys, in order that the distant page machine shall automatically be put into correct receiving conditions.

Later in the paper the author states that the letter and figure shift-keys of the teleprinter effect the spacing between words or groups of figures, but that a different arrangement is adopted in the telegraphic-typesetter transmitter, which in this respect is like a typewriter. Whilst this statement regarding the teleprinter is true of the Type 3A machines which are in use in the inland service and are operated only by Post Office personnel, it does not apply to those teleprinters Type 7 (and they are the greater number in this country) which are used on the private-wire and Telex services. All these latter have a separate space-bar, precisely as in a typewriter, and conform to international standards as laid down by the international consultative committee for telegraphy (C.C.I.T.).

Mr. A. E. Thompson: The intricacies of typesetting by machinery are nowhere greater than in telegraphy, where the problem is to operate a typewriter at great distances over a single telegraph channel. More than 150 different systems have been tried, but it was not until 1910, when the first start-stop teleprinter fitted with a typewriter keyboard appeared, that the fundamental requirements began to be fully understood. Since then, progress in design and construction has been rapid; the telegraph has advanced by leaps and bounds, and its fields of application have been greatly extended. In the particular application described in this paper can be seen all the principal features that have revolutionized telegraphy, and there can be little doubt that it will have a profound influence upon the technique of type composition.

The feature of outstanding importance is the use of automatic tape control, which separates the manual functions of composing from the mechanical functions of casting. The output of the line-casting machine is no longer dependent upon the ability of the operator to maintain a high and uniform speed, and therefore the machine can be operated continuously at its maximum speed instead of intermittently as in the case of direct keyboard working. On the other hand, the operator is no longer restricted by the speed limitations of the line-casting machine and, being provided with the fastest of all typewriter-keyboards used in printing telegraphy, he can attain the high speeds of the skilled touch-typist. The top speed of the keyboard perforator is no less than 900 key-strokes a minute. Valuable time is also saved by the novel and rapid means of justification provided on the keyboard; and the operator can work under ideal conditions, away from the noise and clatter of heavy machinery.

By the introduction of rhythmic touch-typing methods, telegraph administrations have more than doubled the output of their operators, and the savings in labour costs have therefore been very substantial. Experience has shown that similar economies can be obtained with telegraphic typesetting, as the operators can maintain without difficulty an average speed of 350 to 400 key-strokes a minute. In addition, the system makes possible important savings in plant costs; for whereas with manual control the average output of a line-casting machine is only about 4 lines a minute, a constant output of about 8 lines a minute can be obtained with automatic tape control. It is of interest to note also that the system employs the shortest possible code for the number of characters that has to be handled, and therefore it is very economical in the use of paper tape. For these reasons, I think it is most important that attention should be focused upon the economic aspects of the system rather than upon the purely telegraphic facilities it provides.

Mr. F. H. Maynard: I think that Mr. Nancarrow, in referring to counting in ordinary telegraph practice, is perhaps rather confusing this with the facility provided in telegraphic typesetting, where the counting has to be very much more highly developed and accurate than is

the case ordinarily. Perhaps the author would enlarge upon this point.

Mr. A. F. Shaw: It has been mentioned that the teleprinter will handle 900 key-strokes a minute. Will the telegraphic typesetter handle that number, and is the speed of operating entirely limited by the typesetter?

Mr. J. R. Waller: The telegraphic-typesetting signals clearly have to be transmitted over great distances under adverse weather conditions at certain periods of the year, and in view of the risk of breakdown it would appear to be necessary to allocate a substantial outlay to standby plant to permit manual operation. Is this assumption correct, or can the Post Office guarantee a 100 per cent service from London to Scotland during the hours that the newspaper has at its disposal to obtain the matter for the next day's issue?

Mr. D. Murray (France) (*communicated*): The paper is valuable because it serves to remind us that, in addition to strong-stream and weak-stream technique, there are controlling electro-mechanisms of the most remarkable character, correctly described as electrical typewriter-keyboard machines of great complexity and beauty.

The Teletype, one of these keyboard miracles, of which the fundamental characteristic is the transmission of intelligence by semi-mechanical machines (the telegraph class of mechanisms) is in wide use in the form of a telegraph exchange analogous to a telephone exchange covering the whole of the territory of the United States, with about 15 000 subscribers. Considerable progress was being made in this direction in Great Britain also, and plans were being considered for spreading this telegraph keyboard exchange system all over Europe. Unfortunately this development has been interrupted by the war.

The paper deals with an astonishing extension of the telegraph-keyboard mechanism that combines the typewriter-keyboard mechanism with typesetting at a distance. I saw it in operation at the Western Electric Teletype factory in Chicago about 3 years ago. It was shown to me as an example of successful prophecy, because about 40 years previously I had exhibited a typewriter telegraph of this class at the old Astor House in Lower Broadway, with the slogan "This tape sets type." I had brought the model from Australia, and it attracted much attention.

Mr. F. R. Thomas (*communicated*): Although the author has dealt with the requirements and method of operation of the special counting mechanism provided on the keyboard perforator, its fundamental purpose has not been sufficiently stressed. It is the keystone between the composing keyboard perforator and the automatically-controlled line-casting machine, without which telegraphic typesetting would be impossible.

In the description of this mechanism one finds some difficulty in relating the description of the method of eliminating the counting of functions given on page 410 with its associated diagram, Fig. 17, largely because the width of the notch N is not shown correctly. It should be wide enough to include the stop blade ahead of the zero position as well as the one actually in the zero position. The stop blade previously selected for the function keys will then remain set as described.

On page 422 the author refers to the possibility of using a start-stop code of 10 units and suggests that, in order to avoid a reduction in margin, it might be advisable to run both distributors at the same speed and provide for a definite stop at the sending end. As the advantage of such an arrangement over normal start-stop methods is not immediately apparent, perhaps the author will amplify this statement.

Mr. H. H. Harrison (*in reply*): Mr. Morris's remarks are very interesting, as they show clearly the economic advantages of telegraphic typesetting under the conditions he describes. I note with interest that in his opinion telegraphists make better operators than compositors. A possible explanation of this is that touch-typing operation is not applicable to the Linotype machine, since the keyboard layout is quite different from that of a Universal keyboard and a compositor who has been all his life accustomed to the Linotype keyboard cannot readily take up a new system of fingering. A Monotype operator would probably adapt himself rapidly to telegraphic typesetting.

With Mr. Thompson's remarks I entirely agree. From the opportunities I have had of observing this system in operation I can confirm all he says.

With regard to Mr. Maynard's remarks, I cannot see where it is possible to add to the description of the integrating counter or the need for it. The type bodies are varying multiples of a certain unit of type-body width, and these multiples have to be totalled and not merely the number of types in a line of composed matter.

I would remind Mr. Nancarrow that the subject of telegraph transmission has been very thoroughly dealt with before The Institution and, so far as the line is concerned, the remote control of a line-casting machine is purely a telegraph matter. The warning-bell signal applied to telegraph keyboards, typewriters and typesetting machines is a counting mechanism. It does not indicate the actual number of letters which have been set up but the approach to the maximum number which may be set up before the end-of-line signal is transmitted, where this is necessary. This is, of course, not required when transmitting to a tape recorder.

I am aware that a separate space-bar is applied to certain keyboards, thus making their operation similar to that of a typewriter, and I should have stated this in the paper.

As regards Mr. Shaw's question, the telegraphic typesetter cannot be operated at the maximum speed of a telegraph keyboard. The economic advantage of perforated-tape control lies in the fact that, once the tape has been produced, the typesetter operates at maximum possible speed. There are no pauses between letters as is the case when the machine is manually controlled.

For Mr. Waller's information I would explain that transmission between London and Scotland is effected over underground cables and, with the methods adopted, the number of channels available is so great that a total breakdown of communication is inconceivable. The telegraphic network of this country is such that alternative routes could, even in the event of a regional breakdown, be brought into use.

Mr. Murray's 40-year-old prophecy is an interesting example of the slow growth of ideas. Although the Monotype keyboard producing a perforated tape and

provided with an integrating counting mechanism was then available and was also remotely situated from the type producer—the caster—as is the present telegraphic-typesetter keyboard, yet it is only comparatively recently that telegraphic typesetting has been accomplished. Many inventors produced telegraph-typesetting schemes employing start-stop synchronism, but they adopted either the Monotype 30-unit or some similarly unwieldy telegraphic code and their schemes were wrecked fundamentally.

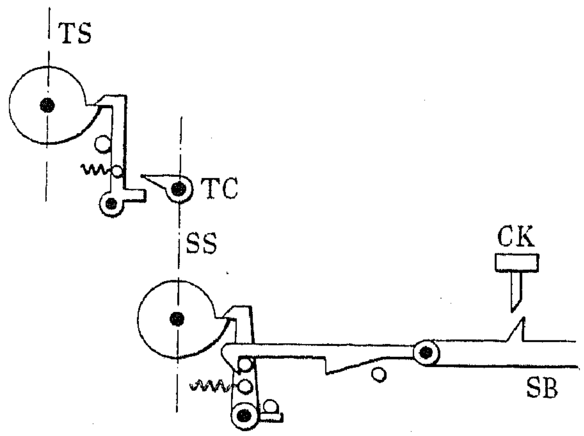

Fig. A

I cannot agree with Mr. Thomas that the application of the integrating counter is insufficiently emphasized, since on page 403 it is stated that it is the addition of this counter to the telegraphic keyboard which has made practicable the setting of type in a line-casting machine over a telegraph channel.

He is correct when he points out that the notch N in Fig. 17 should be wide enough to include the stop-blade ahead of the zero position as well as the one actually at zero.

The transfer of the stop interval from the receiving to the transmitting end has been proposed both in America and in Germany. The advantage of the arrangement is that signal distortion due to the phase difference required in normal start-stop operation is eliminated. The arrangement is diagrammatically indicated in Fig. A. When a character key CK is operated, the start bar SB releases a slow shaft SS carrying a trip cam TC. After an interval of time which is adjustable by orientation of the trip cam, the trip cam starts up the transmitter shaft TS. The diagram, Fig. B, shows the time relationship. T is the time of a single revolution of the slow shaft and t that of the transmitting shaft. The pause interval t' is such that the receiving shaft always stops between letters whatever the slight differences of speed which it and the transmitting shaft may undergo.

Provided that the time to operate the start mechanism at the receiver lies within the limits of the duration of the start impulse, the two distributors are in much

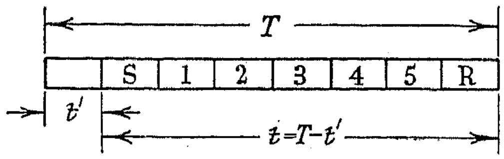

Fig. B

closer synchronism than with the normal method of operation.

With the standard method of operation and assuming knife-edge selection, the upper failure point is a phase difference of one signal element, a speed difference of 14·28 %. The lower failure point is no phase difference, in which event the stop element vanishes. The mean of the two extreme conditions is 7·14 % speed difference. The signal distortion which would otherwise result from this speed difference is to a great extent overcome by orientation means at the receiver, but this is an additional adjustment and one that has to be varied from time to time.

INSULATION STRESSES IN TRANSFORMERS, WITH SPECIAL REFERENCE TO SURGES AND ELECTROSTATIC SHIELDING

By H. L. THOMAS, B.Sc.(Eng.), Associate Member.*

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SUMMARY

The paper discusses various types of abnormal voltage-stresses in transformers, and in particular those due to surge phenomena. A brief résumé of the theory of the effects of surge voltages on transformer windings is given, and a method of determining initial impulse-voltage distribution by means of a calculating board is explained. The principles of electrostatic shielding are considered and the application of a simple, economical and effective type of shield to commercial transformers is discussed. Illustrations of actual transformers fitted with such shields are given, and the efficacy of the shielding is demonstrated by means of cathode-ray oscillograms.

An account is given of researches carried out by means of the recurrent-surge oscillograph, and results are compared with those obtained at high voltage, using a continuously evacuated cathode-ray oscillograph.

In conclusion, reference is made to the problem of co-ordination of insulation, and the relative merits of various protective measures are briefly discussed.

It is shown that a shielded-winding transformer, when properly co-ordinated with line protective devices, possesses a high degree of immunity from breakdown due to lightning or other transient voltages.

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Appendix 1. Methods of Calculating Capacitance Value for " Non-resonating " Shields.

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(1) NORMAL INSULATION STRESSES IN TRANSFORMERS

Under normal working conditions, the voltage stresses to which transformer insulation is subjected are quite obvious; the stress on the " major " insulation (i.e. h.v. winding to l.v. winding and earth) being the working potential of the high-voltage winding to earth, whilst the inter-turn and inter-coil stresses are proportional to the normal working volts per turn. The characteristics of insulating materials under power-frequency voltage stress are now well known, and the design of a transformer to withstand normal working conditions alone would constitute a fairly straightforward problem. The use of oil in the dual role of a liquid dielectric and a cooling medium introduces one disturbing factor, however, because the oil is almost invariably used in conjunction with solid insulation. The dielectric constant of transformer oil is about one-half that of most of the solid insulation material commonly used in transformers, so that when the two are used in series the stress on the oil is about twice that on the solid. The electric strength of the solid insulating material being considerably higher than that of transformer oil, this division of stresses is, unfortunately, the wrong way round. Consequently, care must be taken to ensure that the oil is not over-stressed. In particular, special attention must be given to the avoidance of concentrations of stress, which are likely to set up corona. An incidental advantage of the use of the non-inflammable dielectric liquid known as " Pyranol " or " Permitol " is that the stress distribution is improved, owing to the approximate equality between the dielectric constant of this liquid and that of the solid insulating material.

The normal working voltage per turn on even the largest transformer is not likely to exceed about 150 volts.

It is thus immediately apparent that the amount of inter-turn insulation to comply with normal working requirements alone would be much more than adequately provided by the minimum considered necessary mechanically. To some extent also, the same is true of the insulation between winding sections or coils, and, in the case of multi-layer bobbin coils, of the insulation between layers. The size of the oil duct between sections might of course be dictated by thermal considerations, which also might determine the number of sections in a bobbin-coil winding. Consequently, it is in general the major insulation which is decided mainly by normal voltage stresses, and since it has always been possible to demonstrate the strength of transformer insulation to earth by means of the power-frequency high-voltage test, the amount and arrangement of major insulation to withstand such tests is now well established and has undergone comparatively little change in the last decade. Actually the established standards of high-voltage test, originally empirical and based on power-frequency operating conditions, have resulted in major insulation which has proved itself generally adequate by satisfactory service records even in districts subject to severe lightning.

(2) ABNORMAL INSULATION STRESSES IN TRANSFORMERS

(a) Power-frequency Voltages

A condition under which a transformer may be subjected to excessive over-voltage at power frequency is that arising from an earth fault on one phase of a system having the neutral isolated or else earthed through an arc-suppression coil. This gives rise to full system voltage between each of the two sound phases and earth. Thus for a standard 1-minute high-voltage test of approximately twice the rated system voltage, the abnormal voltage would be one-half of the test voltage.

From available data on the voltage/time characteristics of typical transformer insulation, it is possible to obtain approximately the length of time for which such an abnormal voltage could be applied without causing any effect greater than that corresponding to the 1-minute test. Allowing for an average life of about 20 years for a transformer, it can be deduced that the transformer could be subjected to these abnormal conditions for a 10-hour period, not more than once in every 3 months. This of course is only an approximate estimate and presupposes that the oil and the insulation are maintained in good condition.

For transformers which are required to work continuously under the condition of one line earthed, increased levels of insulation are obviously desirable and such are specified in B.S. 171—1936.

(b) Surge Voltages

The two principal sources of transient over-voltages on transmission lines are lightning and switching. Of these, the former is probably the more important and is responsible for the most severe abnormal voltage-stresses to which transformers may be subjected in service.

Switching surges are, in general, of relatively low amplitude and represent comparatively low rates of change of voltage. Statistics gathered from observations on high-voltage transmission systems over a number of years[3, 4] show that on these systems about 93 %–95 % of all surges originating from causes other than lightning have crest values less than 4 times the crest value of the normal working voltage of the system to earth. Values up to 6 times normal have been recorded, but their occurrence is very rare.

Considering a transformer designed for the standard insulation test of twice system voltage plus 1 000 volts, the 1-minute test is approximately 3·5 times the working voltage of the system to earth. The average value of switching surge voltage in terms of the normal working voltage to earth is probably well below 3·5, so that it could safely be assumed that the average switching surge voltage is of lower amplitude than the 1-minute test voltage on the transformer. The average duration of the switching surge, however, may only be of the order of a quarter-cycle of power frequency, i.e. about 1/200th sec. It would thus require 200×50 (= 10 000) such surges to make up a total period equivalent to the 1-minute insulation test, and it is clear from this that switching surges do not, in general, constitute a very serious source of danger to transformer major insulation. Furthermore, at the frequencies associated with switching surges no excessive internal stresses are set up, the voltage distribution between turns and coils being substantially as for power-frequency voltage.

Lightning disturbances, as is now well known, give rise to transient voltages having both high amplitude and rapid rate of rise. Surge voltages produced by lightning are frequently limited only by the electric breakdown strength of the insulation on the transmission line, and amplitudes as high as 15 to 20 times the peak value of the normal system voltage to earth are sometimes encountered.

(3) Impulse-voltage Stresses in Transformer Windings

The general theory of impulse-voltage distribution in transformer windings is now well known, and has indeed been dealt with quite recently in Institution papers[1, 2], and elsewhere. To summarize briefly, the voltage distribution throughout a transformer winding, following the application of an impulse at the line terminal, is due initially to electrostatic fields, determined by the relative values of the capacitances between adjacent turns and coils, and those between the winding and earth. The curve of initial impulse-voltage distribution is typified by the curve shown in Fig. 1, which also shows a simple equivalent circuit for the transformer winding. For a perfectly uniform winding, this initial impulse-voltage distribution may readily be determined mathematically, provided that the ratio of the above-mentioned capacitances is known. If, however, there is any non-uniformity in the winding arrangement, such as is usually found in practice, due to the use of reinforced end-turn insulation and increased insulation between end coils, then mathematical analysis becomes much more difficult. In such cases, the work is greatly simplified by the use of a calculating board, such as that described in Section (4).

Obviously, increased end-turn insulation results in reduced capacitance between end turns and coils, and a reduction in the number of turns per coil at the line end

as compared with the rest of the winding. Both of these factors react adversely upon the initial voltage distribution and produce increased concentration of voltage at the line end, which tends to neutralize, to some extent, the advantage of the higher electric strength of the reinforced end insulation.

Following the initial distribution, there is a series of complex oscillations involving the capacitances and inductances in the winding network, during which the transition from the initial to the final distribution takes place. For a full discussion of this phenomenon, reference should be made to an Institution paper previously mentioned.[1] During such oscillations, parts of the winding other than at the extreme line end are stressed more highly than during the initial distribution, and the manner in which the maximum inter-coil stress occurs

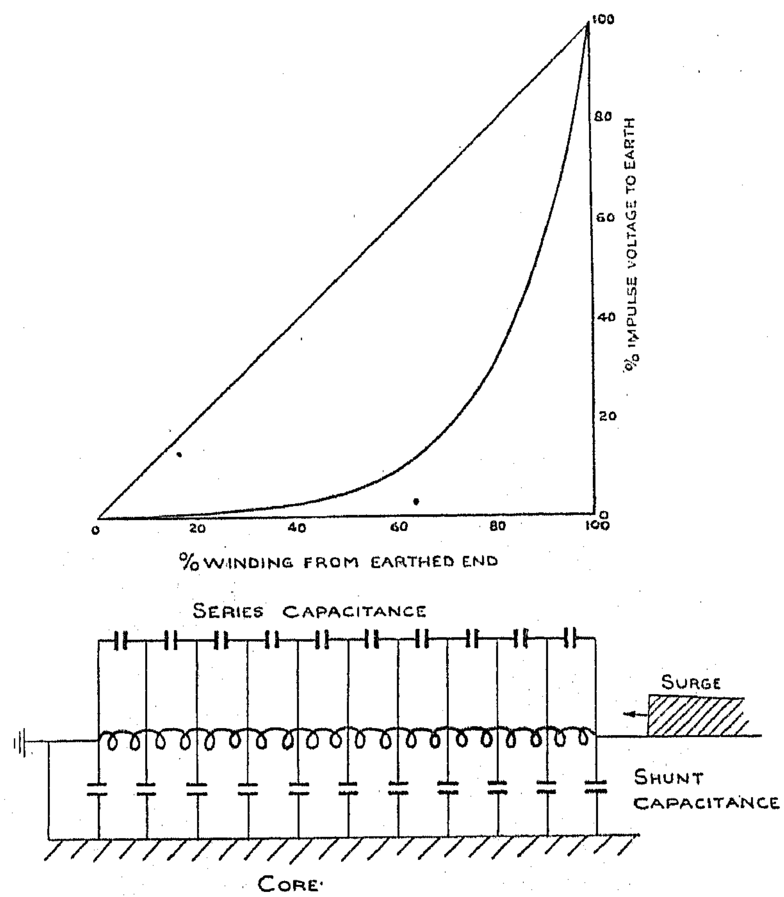


Fig. 1.—Initial impulse-voltage distribution and equivalent circuit of transformer winding.

later and later in progressing through the winding is illustrated in the oscillograms reproduced in Figs. 12 and 13 and also in Fig. 16 (see Plate 2). The oscillations may be regarded as being due to a collapse of the initial voltage distribution curve on to the line of final or uniform voltage distribution, and may conveniently be analysed by considering the deviation of the initial curve from the uniform. The space harmonics of such a deviation curve determine the amplitudes of corresponding harmonic voltages throughout the winding, and it is due to the higher orders of these that the high internal stresses are produced. It is thus apparent that any improvement in the initial impulse-voltage distribution will be accompanied by a reduction in the number and amplitudes of the space harmonics, with consequent reduction in oscillation voltage-stresses. This principle is utilized in the shielded winding, which is described in this paper.

(4) USE OF CALCULATING BOARD

In order to be able to determine rapidly the impulse-voltage distribution in any winding, even if the latter is not uniform, the author's firm has developed a special adaptation of the well-known short-circuit calculating board. The method consists in setting-up a network in such a manner as to approximate closely the impedances of the capacitance network of the transformer. Upon the application of voltage between the line end of this equivalent network and earth, the resulting currents will produce steady voltages throughout the network proportional to those impulse voltages which would initially be established in the actual transformer winding on the incidence of a rectangular-fronted impulse voltage. The voltage at any point in the calculating-board network is readily measured by means of a potentiometer-type detector, arranged to read directly as a percentage of the voltage applied to the line end. A photograph of this equipment is shown in Fig. 25 (Plate 4).

In applying the calculating-board principle, it is unnecessary and indeed usually impracticable to attempt to represent the capacitance between every turn in the

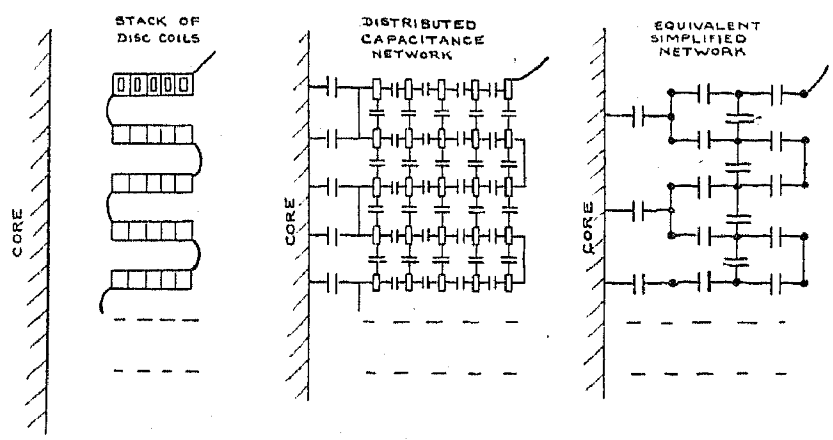


Fig. 2.—Capacitance network of disc-type transformer winding.

winding and adjacent parts. In general, except for coils of very large radial depth, it has been found to be sufficiently accurate to represent only the two essential elements, i.e. capacitance between adjacent coils and capacitance of each coil to earth. The capacitance between adjacent coils is represented by a single lumped value as though connected between the mid-points of the two coils. This entails representing the capacitance between the outer turn of a coil and the centre turn, and that between the centre turn and the inner turn, but these values are by no means critical. The development of the equivalent network is shown in Fig. 2.

The representation of the line-end coil capacitance network in some cases requires special attention, especially in the case of coils of large radial depth. In such cases, the single lumped capacitance between the mid-points of the two coils at the line end would tend to exaggerate the steepness of the voltage distribution at the line end. Judicious sub-division of the network at the line end is therefore necessary in such cases, but for the general run of power transformers the simple network is sufficiently accurate. The author once demonstrated this by representing two sections of a winding in full detail, and inserting this detailed group at various points in the network, including the line end. The differences between the

initial distribution curves obtained with the various positions were found to be quite negligible.

In order to set up a calculating-board network for the purpose of determining the impulse characteristic of a transformer before it has yet been built, it is necessary to calculate the various capacitances involved. For this purpose, standardized methods are employed, based largely upon fundamental principles, but modified to some extent empirically as the result of comparison with actual test values.

(5) CAPACITANCE CONTROL OF IMPULSE-VOLTAGE DISTRIBUTION: PRINCIPLE OF SHIELDED WINDINGS

For the types of windings usually employed in modern transformers it is, in general, impracticable to do very much in the way of proportioning the windings, so as to obtain a small value of the shunt capacitance to earth as compared with the series capacitance, and thereby effecting an improvement in the impulse-voltage distribution. This is because there are so many other design limitations to which consideration must be given, such as reactance and losses, and, in the case of large transformers, restriction of dimensions to comply with transport limitations.

Artificial increase of the series capacitance between adjacent coils of a disc or bobbin-coil type of winding is possible by connecting a capacitor across each pair of coils. An extension of this idea of capacitance control is the shielded-winding transformer, in which the capacitor elements are applied direct to the high-voltage winding in a simple and practical form.

(a) "Non-resonating" Transformer

There are several forms of shielded transformer, and the principles are perhaps most readily understood from consideration of the original form, known as the "non-resonating" transformer. In this type, the shields are applied in such a manner as to make the initial voltage-distribution uniform. It is at once apparent that if the initial distribution is the same as the final distribution, then there can be no oscillations, and the stresses throughout the winding will be uniformly distributed, i.e. with no initial concentration at the line end and no high internal concentrations subsequent to the initial voltage-rise. This end is achieved by mounting, outside and around the h.v. winding, suitably proportioned insulated electrodes, all connected to the line end of the winding, as shown diagrammatically in Fig. 3. If the shield is so proportioned that for every coil in the winding it supplies a charging current just equal to the earth capacitance current for that particular coil, then all of the shunt capacitance current will be supplied from the shield and none of this will have to flow through the series capacitance of the winding. (The method of calculation is given in Appendix 1.) Hence the cause of non-uniform voltage distribution is removed, with the desirable results referred to above. Several large transformers of this type have been manufactured by the author's firm, as well as a large number of voltage transformers and small power transformers for 132-kV working. Examples of these are shown in Fig. 4 and Fig. 6 (see Plate 1, facing page 436). Tests were made a number of years ago to obtain the initial impulse-voltage distribution throughout the h.v. winding of a transformer such as that shown in Fig. 4. At the time that these tests were carried out, no cathode-ray oscillograph was available, and so the voltage measurements were made by means of sphere-gaps, a $1\frac{1}{2} \times 40$ impulse wave being used. The results of these tests are shown by the curves of Fig. 5.

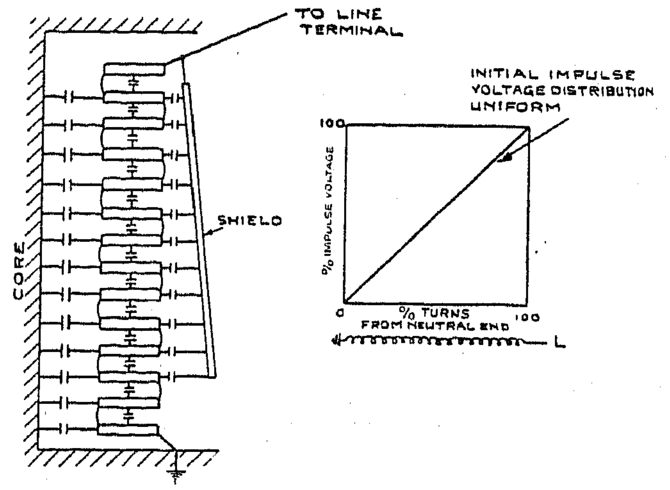


Fig. 3.—Non-resonating transformer: principle of shielded winding.

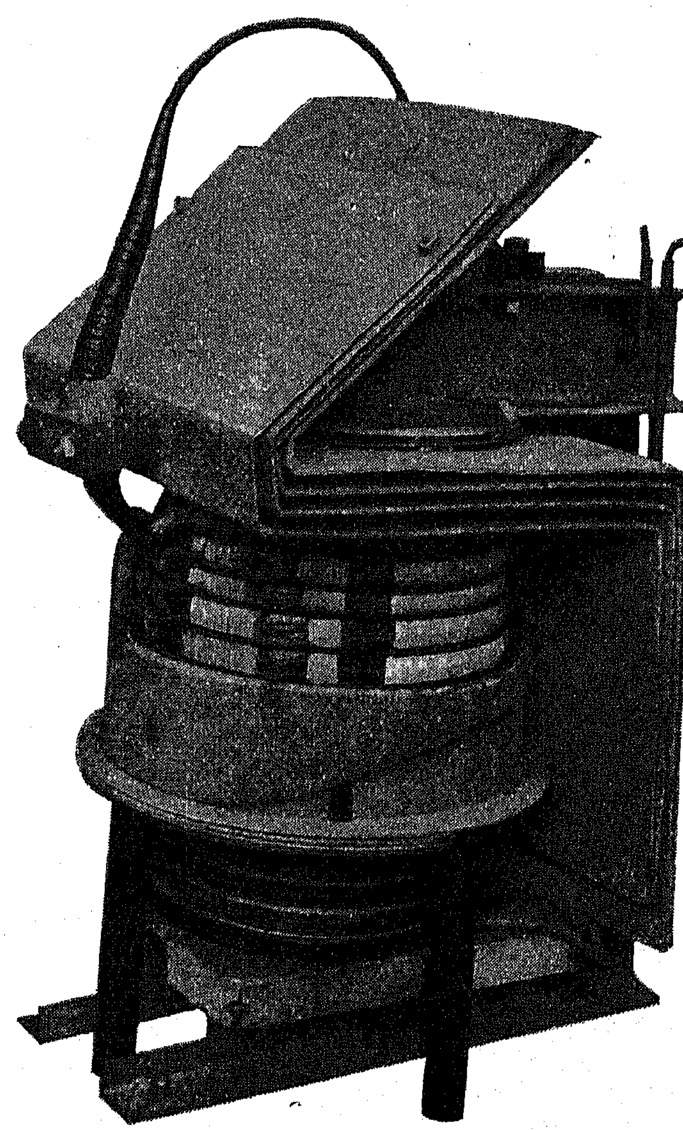


Fig. 4.—Core and windings of shielded voltage-transformer, for use on 132-kV circuit.

An advantage of "non-resonating" shielding is that in the case of a transformer with a solidly earthed neutral, the insulation between h.v. and l.v. windings can be

graded in accordance with linear voltage distribution, with consequent economy, especially in the case of very large high-voltage units. It should be clear that such a procedure would be quite inadmissible in a non-shielded transformer, on account of the fact that during the impulse-voltage oscillations the voltage at every point in the winding rises at some time or other above the value corresponding to linear distribution. This point is illustrated by Fig. 10(*a*), in which space/voltage distribution curves for a non-shielded winding are given corresponding to various time-intervals measured from the start of the impulse.

(b) Simplified Shielding

At the present time, the principal application of "non-resonating" shielding is in connection with transformers for exceptionally high voltages, of the order of 220 kV and above, the impulse level of such transformers being so high that the most complete form of shielding is desirable, in order to reduce internal stresses to a minimum. For relatively lower voltages, i.e. 132 kV and below, a simpler type of shielding has been developed[7] in which the shields

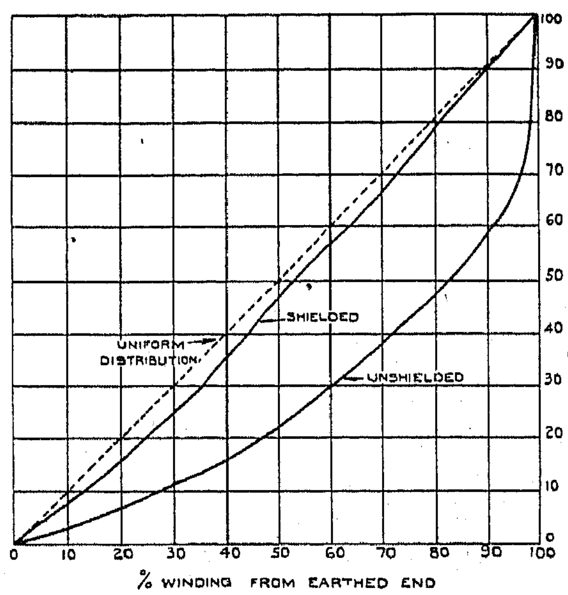


Fig. 5.—Initial voltage distribution on impulse test of 132-kV voltage transformer (non-resonating design).

are arranged so as to improve the initial voltage distribution, without going to the full extent of producing uniform voltage distribution.

The design of the shielding is such that the space harmonics are reduced, and in particular the higher harmonics, with the result that the surge voltage-gradients within the winding are reduced. This procedure is possible with relatively lower-voltage transformers because, although the internal surge voltage-gradients are higher than they would be with uniform voltage distribution, they are related to a lower basic voltage. The result is that the actual stresses are within limits for which the necessary amounts of inter-turn and inter-coil insulation may economically be provided. It is also possible that the minimum amounts of such insulation dictated by mechanical or thermal considerations may sometimes be more than sufficient to withstand the impulse-voltage stresses on relatively low-voltage transformers.

A special application of this principle of shielding for other than uniform initial impulse-voltage distribution is known as "sinusoidal shielding." (The method of calculation is dealt with in Appendix 2). In this case, the shields are designed to produce an initial distribution of which the deviation from the uniform is a half sine wave. In other words, all of the space harmonics excepting the fundamental have been eliminated. This is illustrated by Fig. 7. The internal voltage-gradients are thus only those produced by the fundamental oscillation, and are nowhere and at no time greater than the initial gradient at the line end of the winding. For a fundamental space harmonic amplitude of 32 % the maximum gradient is 2 to 1, or twice that corresponding to uniform distribution. The maximum departure from uniformity occurs at the centre of the winding, where the maximum voltage

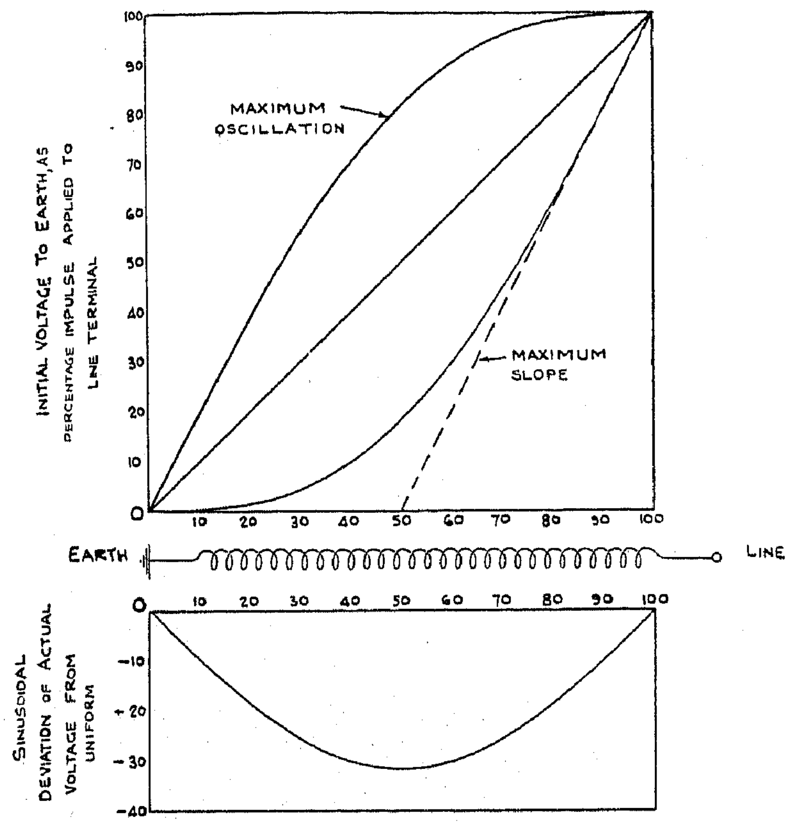


Fig. 7.—Impulse-voltage distribution in winding in which "sinusoidal shielding" is adopted.
Curves drawn for maximum deviation, i.e. 31·9 %.

to earth is theoretically 82 % of the applied impulse voltage. With a greater degree of shielding, the fundamental amplitude can be further reduced, and the maximum gradient will become less than 2 to 1, until, in the limit, the fundamental amplitude becomes zero and uniform voltage distribution, or non-resonating shielding, is secured.

The more general type of simplified shielding, however, aims at reduction rather than elimination of the higher space harmonics, and the amount of shielding required is accordingly less than for either sinusoidal or non-resonating shielding.

The essential feature of the construction is that the shields are not all connected to the line end of the winding, but are sub-divided into sections or "cascades," each being connected to a suitable point within the winding. Typical connections and the arrangement of such shields are shown in Fig. 8. In general, the shields consist of paper-insulated copper conductor, wound around the outside circumference of the h.v. winding. Such shields

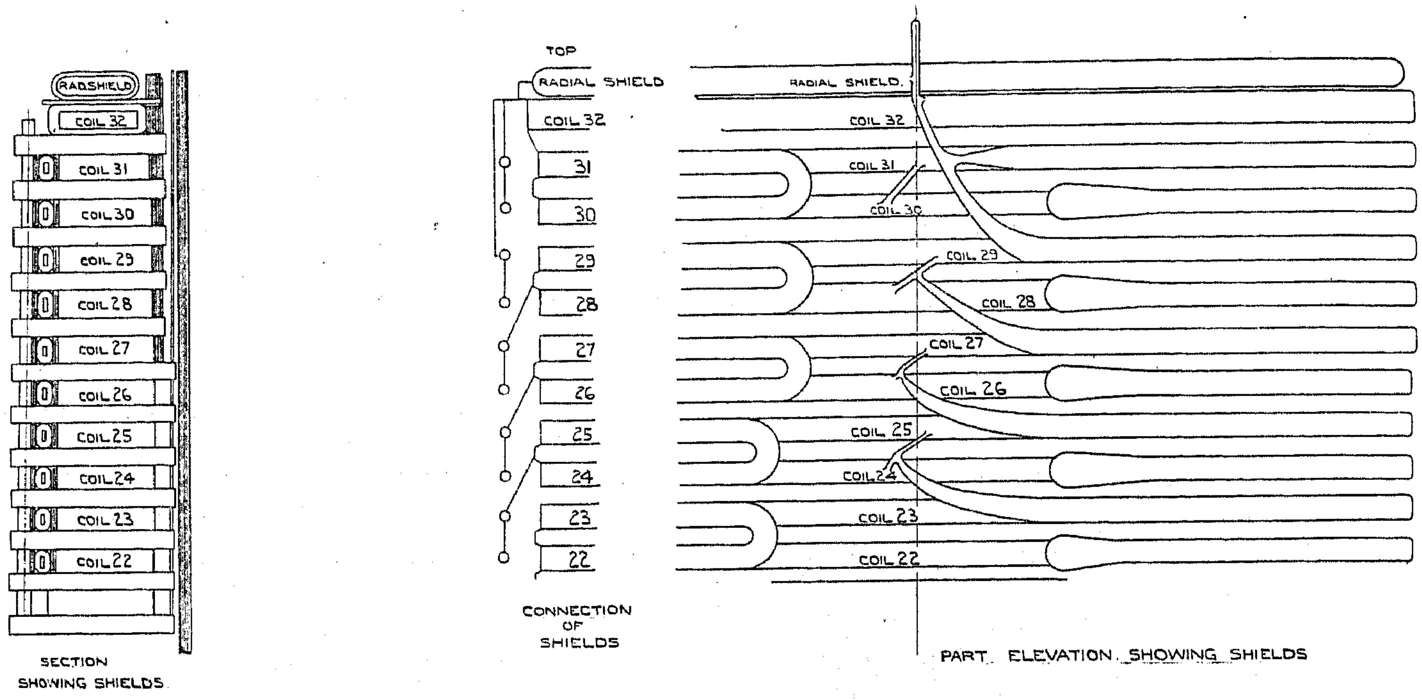


Fig. 8.—Typical arrangement of shields.

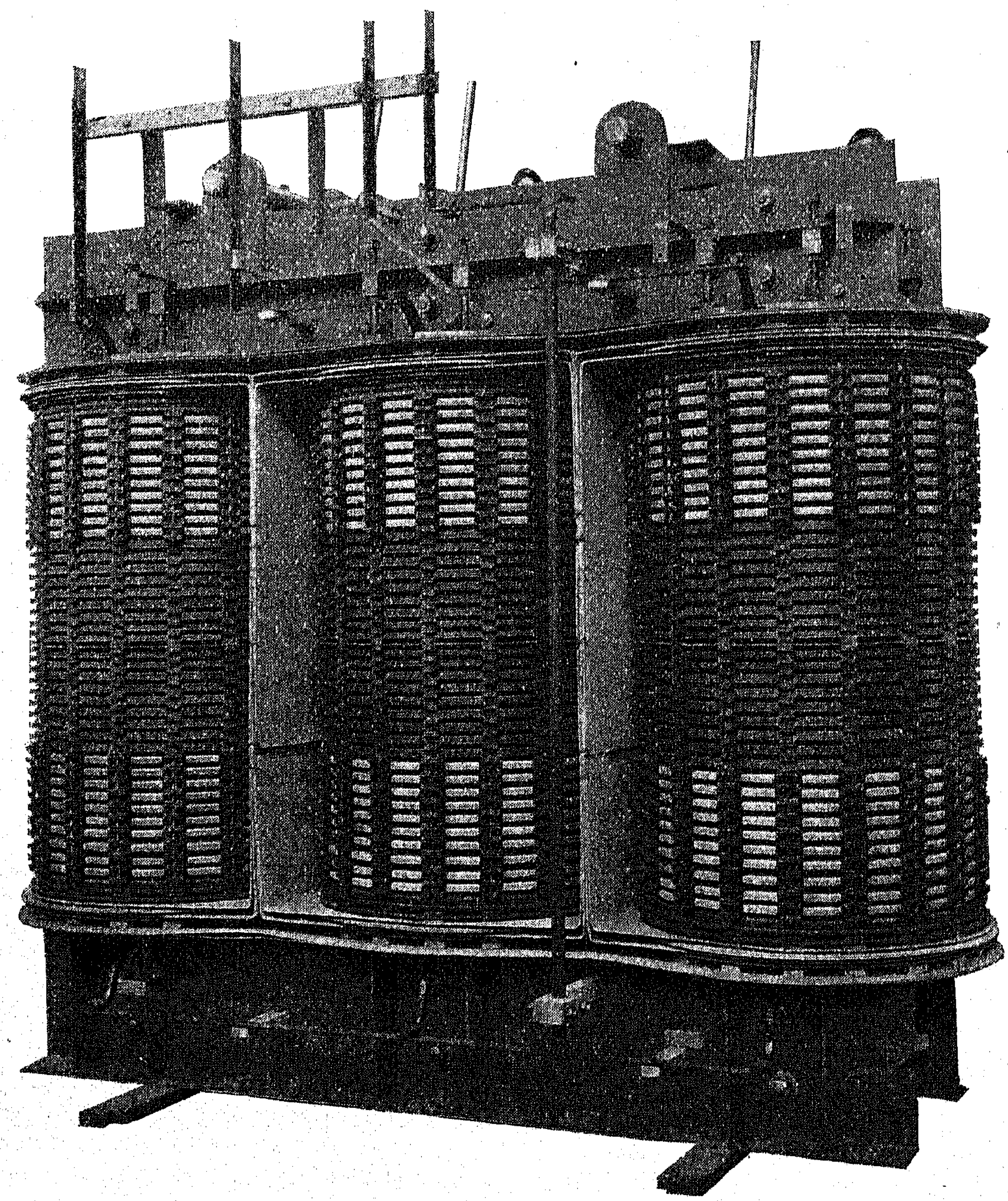


Fig. 9.—Shielded-winding transformer; rated 3-phase, 50 c./s., 8 000 kVA, 88/6 kV. Photograph showing how shields are applied to delta-connected high-voltage windings.

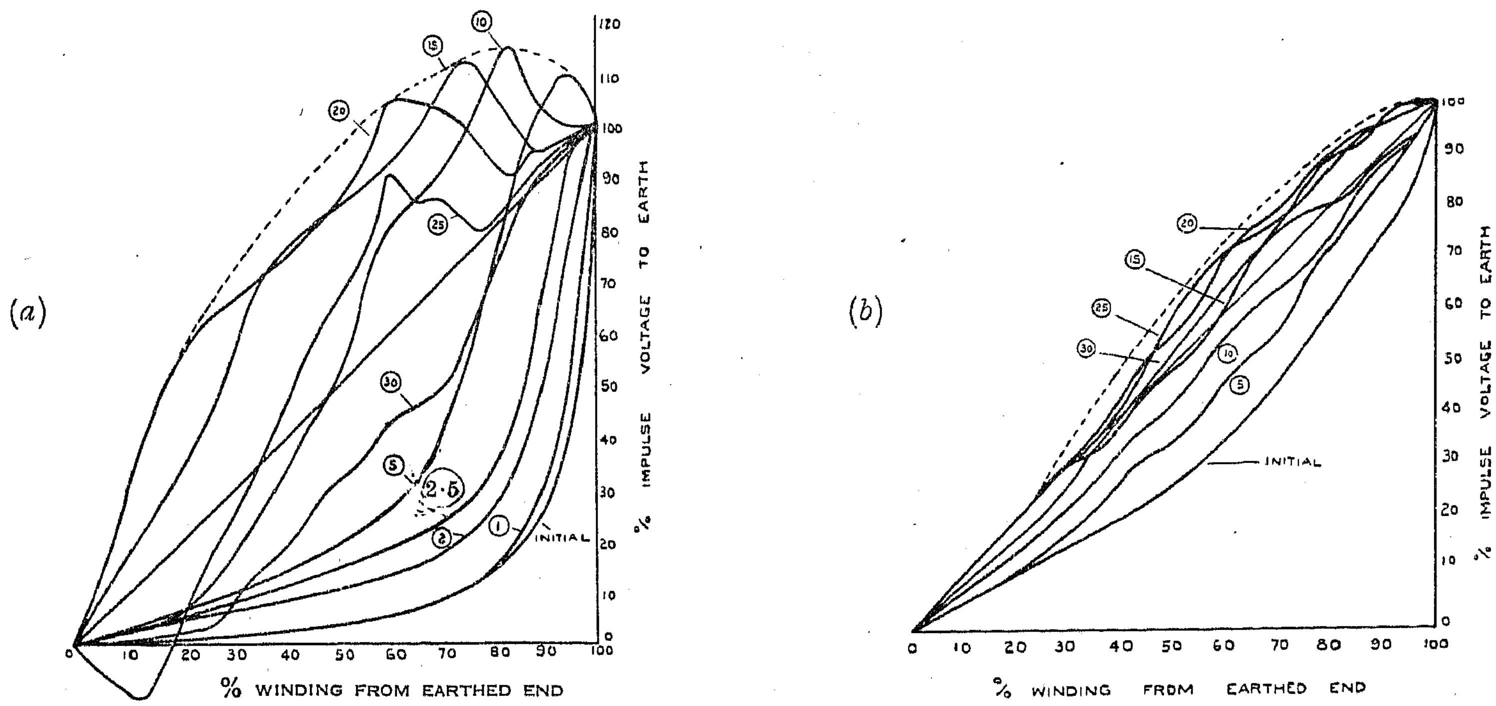


Fig. 10.—Impulse-voltage distribution in shielded transformer winding (neutral earthed). Values obtained from recurrent-surge oscillograph tests on model winding.

(*a*) Winding without shields.
(*b*) Winding with shields.
Figures on curves indicate time in microseconds from start of impulse.

can be applied without materially increasing the overall dimensions of the winding, as will be seen from the example shown in Fig. 9. Furthermore, there are no heating, loss, or short-circuit problems involved, and thus the shields and their insulation can be selected with a greater degree of freedom than in the case of windings. A feature of this type of shielding is that it is equally suitable for delta-connected windings, in which case the shields are applied at both ends of the winding, so as to allow for the possibility of surges striking either end, or even both ends simultaneously. The non-resonating shield is pre-eminently suited to star-connected windings with the neutral end earthed.

For the design of these shields, the calculating board is invaluable, since the shield capacitances and connections can be represented in the equivalent network, and their effect very rapidly determined. Further information on this subject will be found in Appendix 3.

(6) OSCILLOGRAPHIC TESTS ON SHIELDED WINDINGS

(a) General Procedure

A large number of tests have been carried out with the object of checking the efficacy of shields fitted to many different commercial transformers as well as on specially constructed models. Most of these tests have been taken by means of a high-speed recurrent-surge oscillograph.[5] It is more convenient to carry out such tests with the windings in air, so that for the purpose of comparison with the estimated initial voltage distribution, a second calculation is made in which the capacitance values in the calculating-board network are suitably modified to allow for the changed dielectric conditions. The agreement between tested and calculated initial voltage distribution has been good, bearing in mind the nature of the calculations and the limits of accuracy of the method of test. In all cases, the shields have been shown to effect a substantial improvement.

The effect of reduction of oscillations, following improved initial voltage distribution obtained by shielding, is well illustrated by Fig. 10(*b*). This shows the impulse-voltage distribution in a model shielded winding at various times. Corresponding curves obtained on the same winding without the shields are shown in Fig. 10(*a*). It may be of interest to note that the initial voltage distribution curve shown in Fig. 10(*b*) is approaching sinusoidal deviation from the uniform. To illustrate this, the first ten space harmonics have been determined by analysis, and are set out in Table 1. It will be seen that all but the fundamental and the second harmonic have almost negligible amplitude.

Table 1

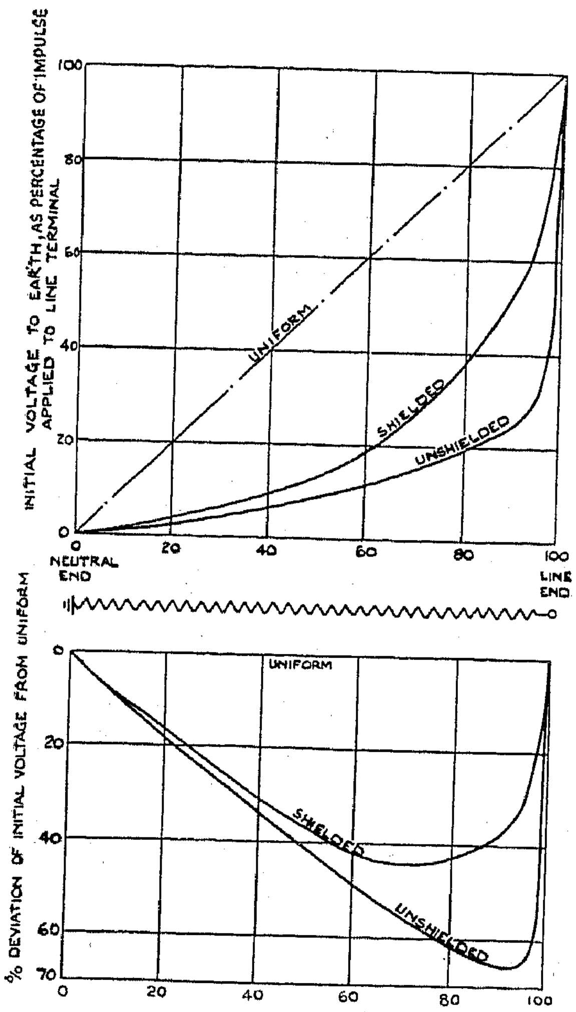
ANALYSIS* OF SPACE HARMONICS OF INITIAL DISTRIBUTION IN SHIELDED WINDING, AS SHOWN IN FIG. 10(*b*)

Order of harmonic	1	2	3	4	5	6	7	8	9	10
Amplitude as percentage of applied impulse	23·0	6·54	1·3	0·67	0·85	0·73	0·40	0·23	0·30	0·19

(b) Tests in Air on a 3-phase 126-kV 1 000-kVA Transformer

Figs. 11 and 12 show results of tests on a 3-phase 50-cycle 1 000-kVA power transformer, having a voltage ratio of 126 kV to 11 kV, both windings being star-connected. Fig. 11 shows the initial voltage distribution as determined from the oscillograph tests. The curves marked " unshielded " were obtained from tests in which

the shields were actually in place, but were disconnected from the winding. Other tests have shown that the coupling capacitance of the shields, even when these are not connected to the winding, has a beneficial effect on the impulse-voltage distribution, and consequently it can be stated that the actual degree of improvement is greater than as indicated by the curves. This applies to most of the tests which have been carried out, and it arises because the shields really form part of the winding and it is desirable that they should be in place whilst the coil stack is receiving its various treatments. Hence it is seldom possible to obtain, for testing purposes, a shielded winding with the shields entirely absent.



Max. value of space harmonics in deviation curve, as percentage of applied voltage.

Order of harmonic	Unshielded winding	Shielded winding
1	50·9	41·6
2	22·4	14·0
3	14·6	7·0
4	10·0	4·6
5	7·5	3·6
6	5·7	2·6
7	4·6	2·1
8	3·4	1·3
9	2·6	1·0
10	1·4	0·64
11	0·56	0·29

Relative effect of harmonics on gradients

Order of harmonic	Unshielded winding	Shielded winding
1	50·9	41·6
2	44·8	28·0
3	43·8	21·0
4	40·0	18·4
5	37·5	18·0
6	34·2	15·6
7	32·2	14·7
8	27·2	10·4
9	23·4	9·0
10	14·0	6·4
11	6·2	3·2

Fig. 11.—Initial impulse-voltage distribution in shielded transformer winding: transformer rated 3-phase, 50 c./s., 1 000 kVA, 126 kV (star)/11 kV (star). Plotted from recurrent-surge oscillograms of test in air.

Fig. 11 also shows the "deviation" curves for both "shielded" and "unshielded" conditions, and the amplitudes of the first eleven space harmonics for both of these curves have been tabulated. Of the two Tables forming part of this Figure, the lower one, giving the product of each harmonic and its order, which is a measure of the contribution of each harmonic towards the voltage gradients within the winding, has been included only to emphasize the importance of the higher harmonics in this respect.

In Fig. 12 the effectiveness of the shields in reducing internal voltages is shown by oscillographic records of the inter-coil voltages for the first seven coils from the line end of the winding. It will be seen that the maximum amplitude of the inter-coil voltage is considerably reduced by the shields. At the line end of the winding, the crest of the first (and maximum) oscillation of the inter-coil voltage approximately coincides with the crest of the applied impulse wave, thus showing that near the

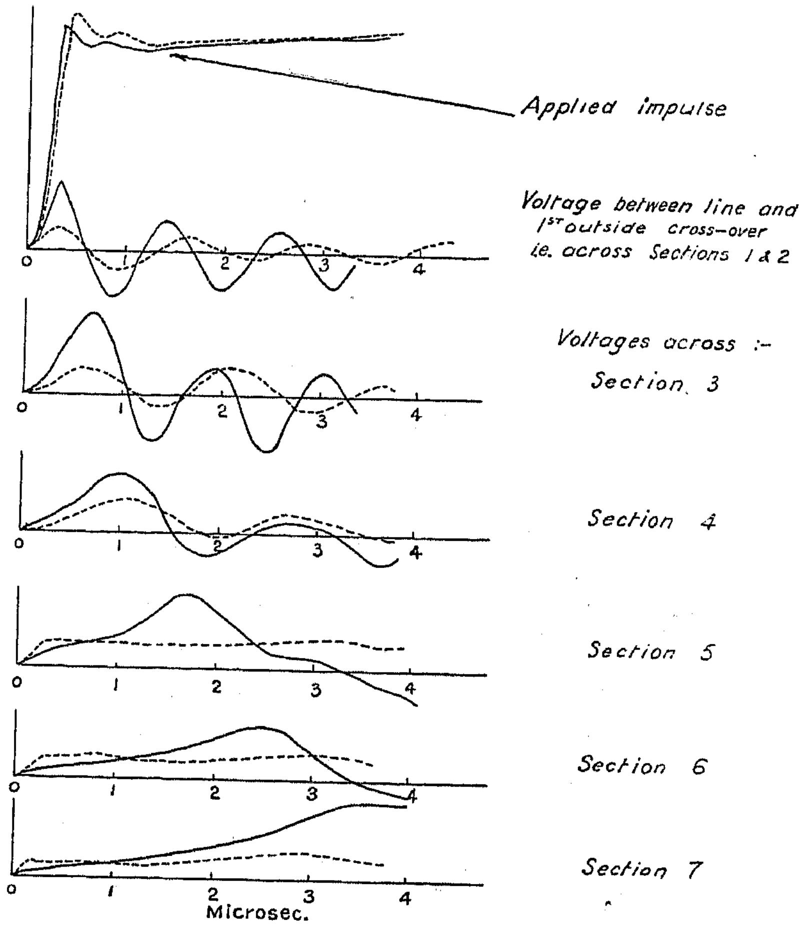


Fig. 12.—Surge-voltage distribution in shielded-winding transformer: inter-section voltages, showing effect of shields. Transformer: 3-phase, 50 c./s., 1 000 kVA, high voltage 126 kV (star), low voltage 11 kV (star).

----- Shielded.
——— Unshielded.

In the case of the unshielded winding, shields were fitted but not connected. The tests were carried out by means of a high-speed recurrent-surge oscillograph with an applied impulse having approximately 0·25-microsec. front and 100-microsec. tail (to half value).

line end the maximum internal gradient occurs initially, which of course is also apparent from consideration of the initial voltage distribution curve.

A numerical comparison between the maximum amplitudes of the inter-coil oscillation voltages, with and without shields, is given in Table 2. The voltages are expressed as percentages of the impulse applied across the whole winding of 100 % turns, whilst the last two

Table 2

Between sections	Max. % volts		% volts ÷ % turns	
	Shielded	Unshielded	Shielded	Unshielded
1–2	11	33	25·6	77·0
3–4	13	40	15·7	48·2
4–5	16	29	19·3	35·0
5–6	14	35	9·7	24·0
6–7	11	25	7·5	17·1
7–8	12	37	3·4	10·7

columns give the ratio of the actual stress to that corresponding to uniform voltage distribution for the same magnitude of surge at the line terminals; or, in other words, the voltage gradient.

It will be seen that the voltage gradients in the shielded winding are less than half those obtained with the shields disconnected. It may be observed that in the case of the shielded winding the gradient between Sections 4 and 5 is greater than that between Sections 3 and 4, which are nearer to the line end. This effect is due to the alteration in the relative capacitances of the shields and winding when the stack is in air, as compared with the proper conditions for which the shields were designed, i.e. for an oil-immersed transformer. Such irregularities can indeed be predicted by means of the calculating board, and have been found to be absent in windings tested in oil. It should be noted that there is no irregularity in the gradients for the unshielded winding in Table 2.

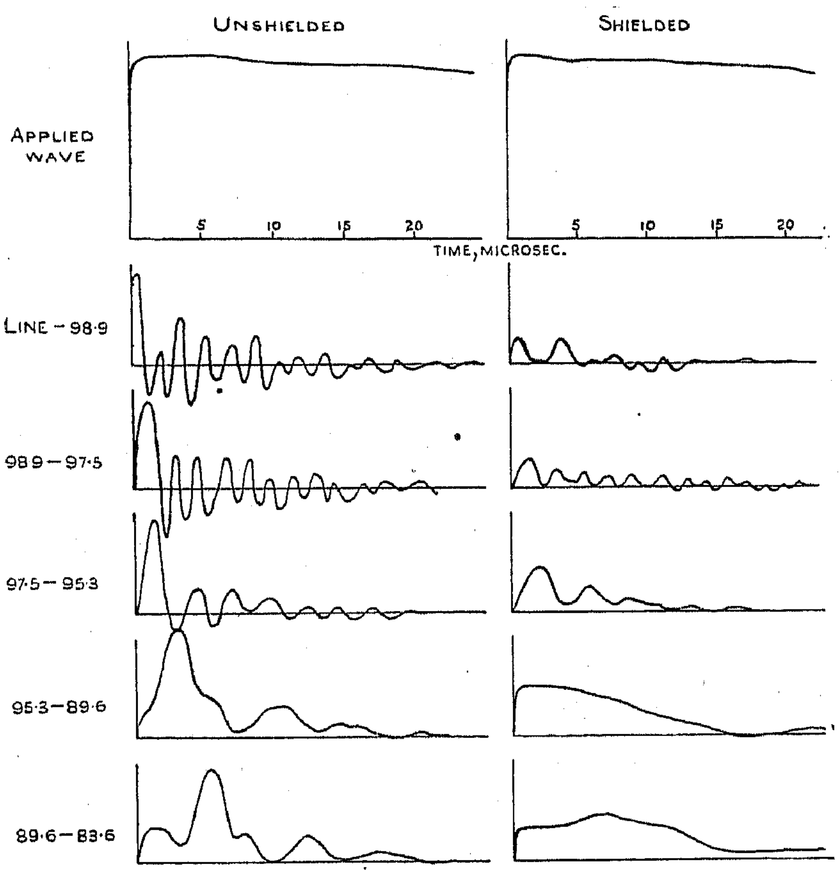


Fig. 13.—Inter-coil impulse voltages with and without shields. Values obtained from recurrent-surge oscillograph tests in oil on a 3-phase 8 000-kVA 88 000/6 000-volt power transformer.

Figures at side refer to percentage of winding from earthed end.

(c) Tests in Oil on a 3-phase 88-kV 8 000-kVA Transformer

For the purpose of these tests, temporary leads were brought out from tapping points in one of the h.v. windings, and from the shields, and the transformer was immersed in oil in its own tank. The primary object of this was to permit of impulse-voltage distribution tests being taken at high voltage, in order to make a comparison with the low-voltage recurrent-surge oscillograph method. The h.v. windings of this transformer were delta-connected, and shields were provided at each end of the winding, as may be seen from Fig. 9. Recurrent-surge oscillograph tests were taken on one phase of the delta-connected windings, under the condition of an impulse incident on one line, and it was found that the surge behaviour of the winding under test was practically the same whether the other line terminals were isolated or earthed. The l.v. winding was short-circuited and earthed during the tests. Some inter-coil voltages obtained from these tests have been reproduced in Fig. 13, from which the improvement obtainable from the shields may be seen. The next Section of this paper contains some tabulated values of the maximum amplitudes of the oscillations.

(d) Impulse-voltage Distribution Tests using High-voltage Impulse Generator and Cathode-ray Oscillograph

Tests were made on one phase of the transformer referred to in the previous Section, the applied impulse

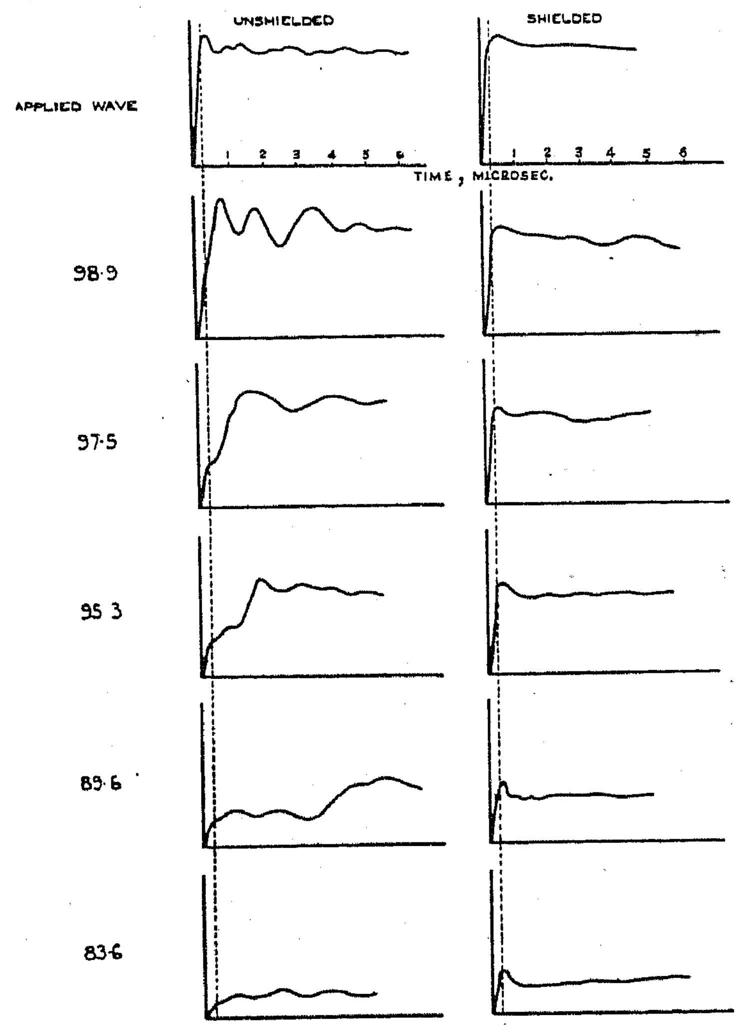


Fig. 14.—Voltages to earth from tests on 88-kV 8 000-kVA transformer, using high-voltage cathode-ray oscillograph. Applied wave: 70 kV (crest), 0·4/100 microsec.

Figures at side refer to percentage of winding from earth end.

voltage being about 70 kV (crest). The wave shape of the applied voltage was arranged to be approximately the same as that used in the recurrent-surge oscillograph tests, though actually the front time, when subsequently determined from the cathode-ray oscillograms, was found to be somewhat shorter. A cathode-ray oscillograph of the continuously evacuated type was used to obtain photographic records of the voltages examined during the tests. All these tests were taken with the remote end of the winding earthed.

The voltage to earth at each of the various tapping points was recorded at both fast and slow sweep speeds of

the cathode-ray oscillograph. The oscillograms taken at the fast speed are reproduced in Fig. 14, both shielded and unshielded conditions being represented. From these, the initial distribution has been determined; the results are shown in Fig. 15, in which the full-line curves were obtained from corresponding tests using the recurrent-surge oscillograph, and the high-voltage test results are shown as points.

The agreement between the two methods will be seen to be very close. The somewhat faster wave-front of the applied voltage in the case of the high-voltage tests may possibly account for the slight difference which does exist between the two curves for the unshielded winding. The effect of differences in the wave-front time is, in general, to reduce the initial concentration of voltage as the time is increased, the "initial" distribution being here considered to be that which obtains when the applied voltage reaches its crest. The modification is brought about by oscillations of the higher space harmonics taking place within the wave-front time, the possibility of this obviously becoming greater with increase of the front time. The effect depends upon whether there are any harmonics in the true initial electrostatic distribution of sufficiently short periodic times to be comparable with the applied wave-front time. This would account for the slightly steeper "unshielded" curve obtained with the high voltage at 0·4 microsec. wave-front as compared with that obtained with the recurrent-surge oscillograph wave-front of about 0·5 microsec. The effect is not so apparent in the case of the shielded-winding curves because of the reduction in the number and amplitude of the higher harmonics, as well as the lengthening of their periodic times (by virtue of the added capacitance of the shields).

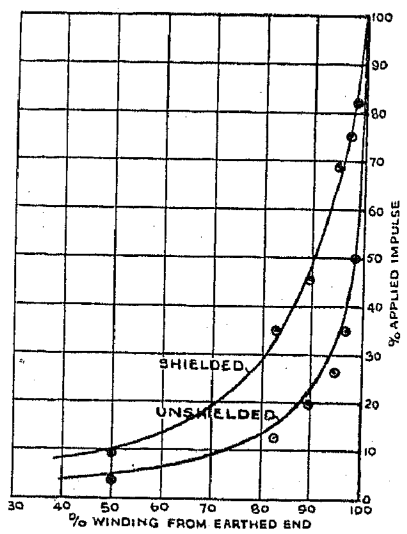


Fig. 15.—Comparison between recurrent-surge oscillograph method and high-voltage impulse test method for the determination of initial impulse-voltage distribution.

(A) Curves represent results obtained from recurrent-surge oscillograph tests.
(B) Points represent results obtained using a 70-kV impulse and a high-voltage cathode-ray oscillograph.
Wave-form of applied impulse { Case (A) 0·5/100 microsec. / Case (B) 0·4/100 microsec.

Inter-coil voltages, showing the effect of shielding, are illustrated by the oscillograms reproduced in Fig. 16 (Plate 2). These cannot be directly compared with corresponding oscillograms obtained by the recurrent method, on account of differences in the scales, although the same general characteristics may be observed. For the purpose of quantitative comparison, therefore, the maximum amplitudes of the inter-coil voltages obtained by both methods are tabulated in Table 3.

The tabulated figures show quite good agreement between the two methods.

Table 3

INTER-COIL VOLTAGES ON 88-KV 8 000-KVA TRANSFORMER: COMPARISON BETWEEN RECURRENT-SURGE OSCILLOGRAPH AND HIGH-VOLTAGE IMPULSE TEST METHODS

Percentage turns from line end		Voltage as percentage of applied impulse			
		Unshielded		Shielded	
		R.S.O.	C.R.O.	R.S.O.	C.R.O.
0 to 1·1	adjacent coils	53	72	16	23
1·1 to 2·48	adjacent coils	49	61	16	20
2·48 to 4·72	adjacent coils	53	54	23	18
4·72 to 10·32	alternate coils	60	61	27	30
10·32 to 16·32	alternate coils	48	41	25	23

R.S.O. = recurrent-surge oscillograph (low-voltage impulses).
C.R.O. = cathode-ray oscillograph and high-voltage impulse.

(e) Effect of Shields in Reducing Stresses due to Chopped Waves

Some tests were made on the transformer referred to in Sections (6)(*c*) and (6)(*d*), using a 70-kV 0·4/100-microsec. impulse voltage chopped on the tail. The sudden collapse of the voltage gives rise to a corresponding abrupt gradient in the coil-to-coil voltages. A few examples of oscillograms showing this effect, with and without shielding, are reproduced in Fig. 17 (Plate 3). The efficacy of the shielding under these conditions is clearly demonstrated.

As a further illustration of the effectiveness of shielding under chopped-wave conditions, Fig. 18 shows two sets of tracings obtained from tests taken with a recurrent-surge oscillograph on a model shielded winding, with the shields disconnected and connected respectively.

These oscillograms show the effect of chopping the applied impulse voltage at various times on the tail of the wave, as well as on the front and at the crest of the wave. It will be seen that the chop produces oscillations generally similar to those produced by the full wave, but in the inverse sense and superimposed upon the latter. Hence, if the chop occurs at the instant when the inter-coil voltage is at a maximum negative amplitude, there is a liability for the resultant negative voltage peak to be greater than the initial peak. This tendency is clearly shown at *e* in Fig. 18, and that the negative peak due to the chop is not still higher may be ascribed to the fact that owing to a slight imperfection in the device used for

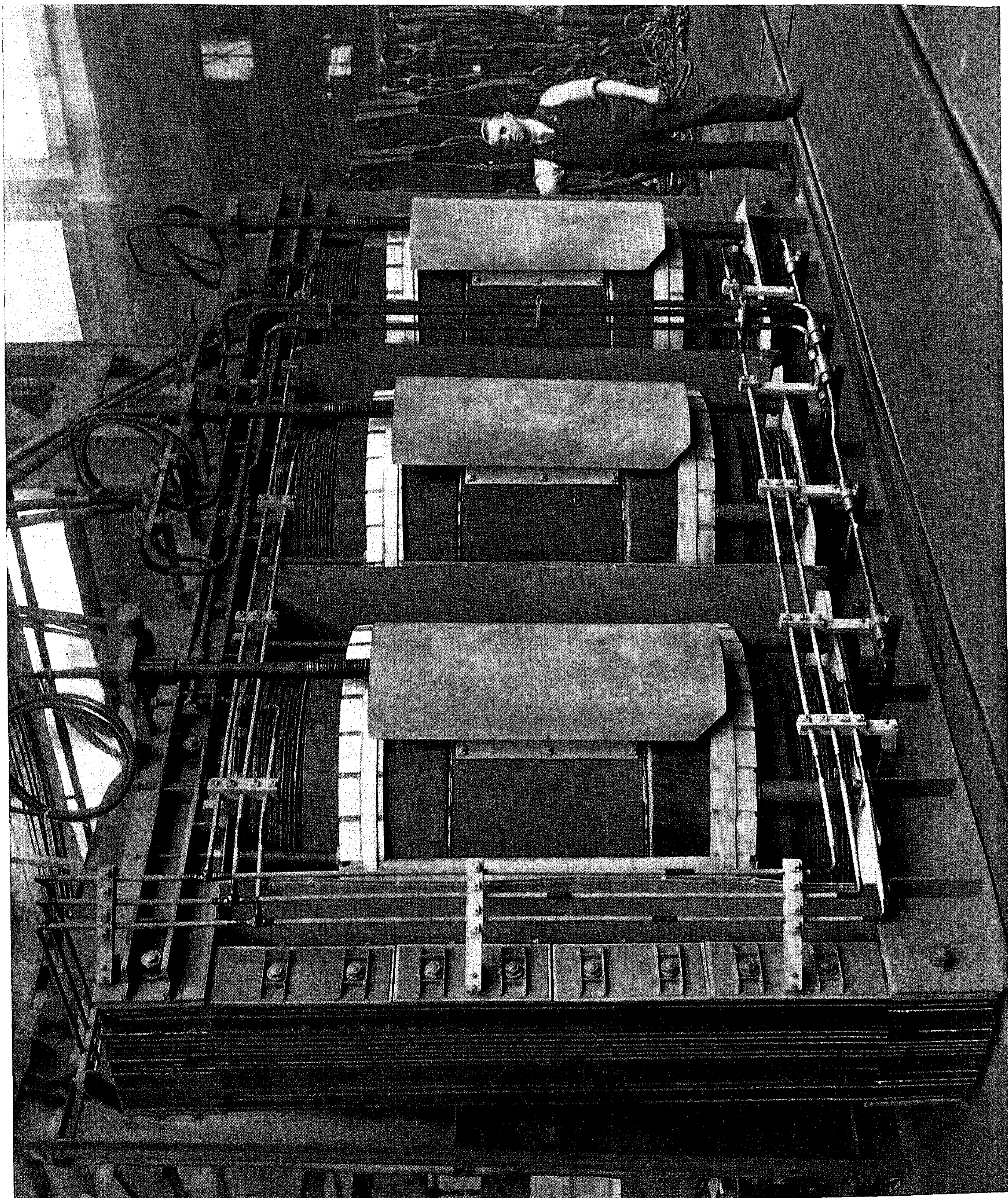


Fig. 6.—Non-resonating power transformer; rated 3-phase, 50 c./s., 30 000 kVA, 132/11 kV.

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Plate 2

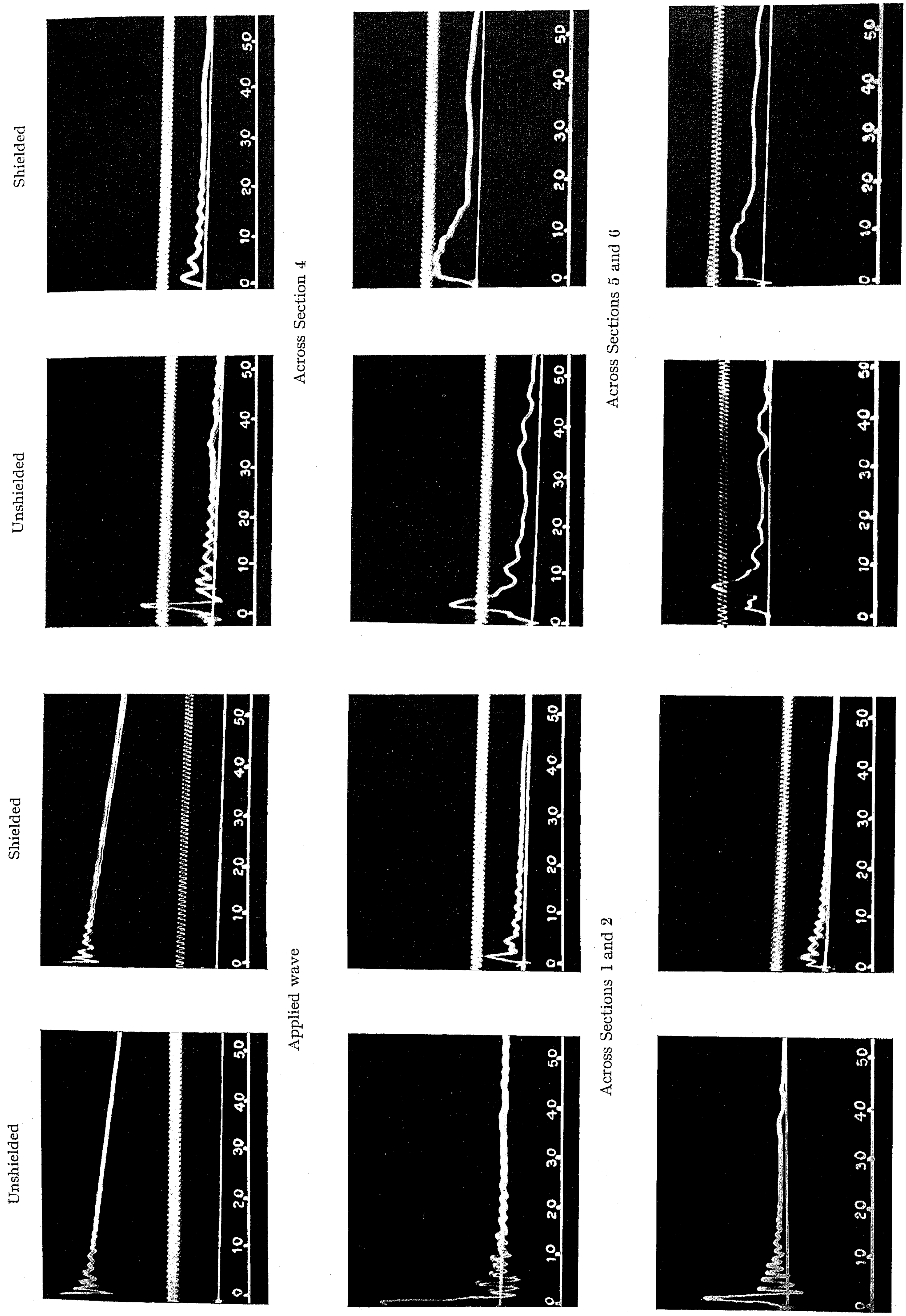
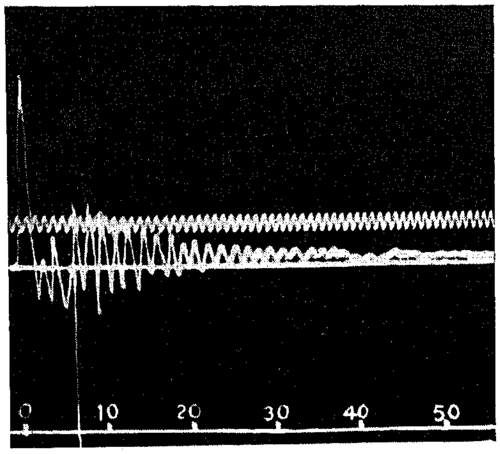
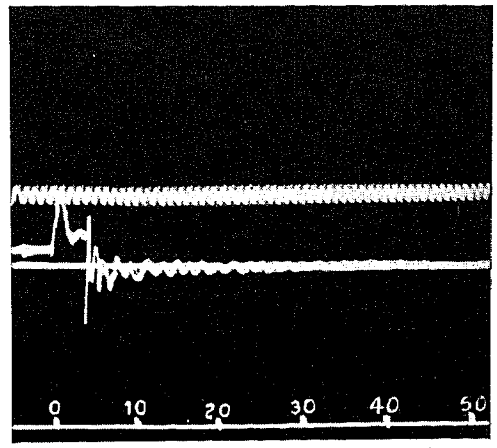


Fig. 16.—Impulse-voltage values across sections of high-voltage winding of 8 000-kVA 88/6-kV 3-phase transformer. Tests in oil using high-voltage cathode-ray oscillograph. Applied impulse 70 kV (crest), 0·4/100-microsec. wave.

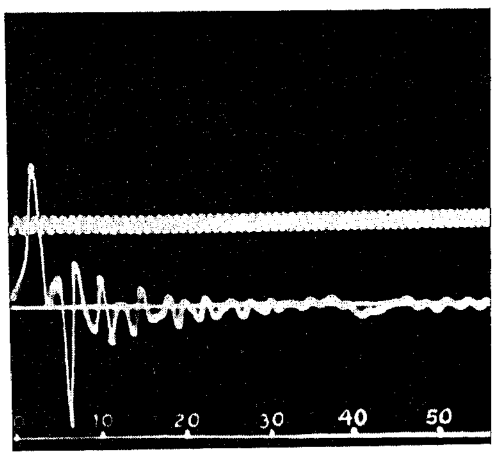
Unshielded

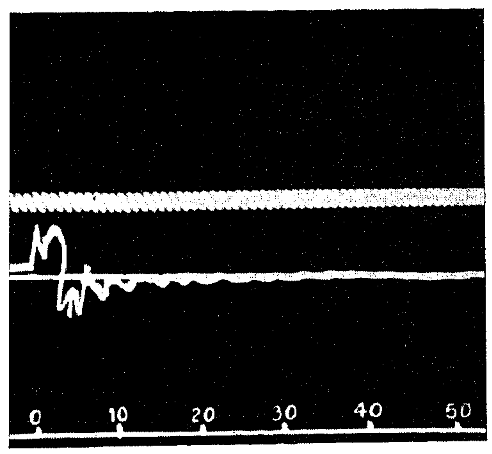
Shielded



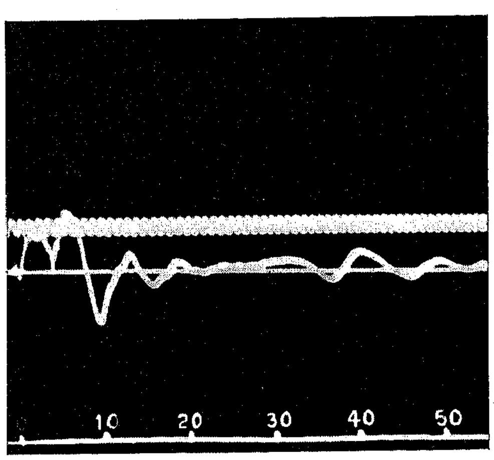


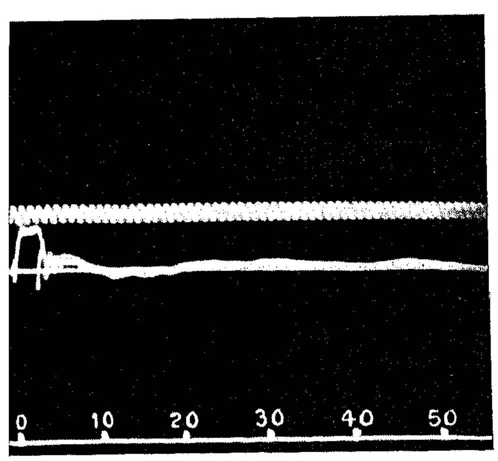
Across Sections 1 and 2 (100 % to 98·9 %)





Across Section 4 (97·5 % to 95·3 %)





Across Sections 7 and 8 (89·6 % to 83·6 %)

Fig. 17.—Impulse-voltage values across sections of high-voltage winding of 8 000-kVA 88/6-kV 3-phase transformer. Oscillograms showing effect of chopped-wave impulse. Tests in oil using high-voltage cathode-ray oscillograph. Applied impulse 70 kV (crest), 0·4/100-microsec. wave, chopped on the tail.

The percentages at the left of the oscillograms refer to the percentage of the winding from the earthed end.

Plate 4

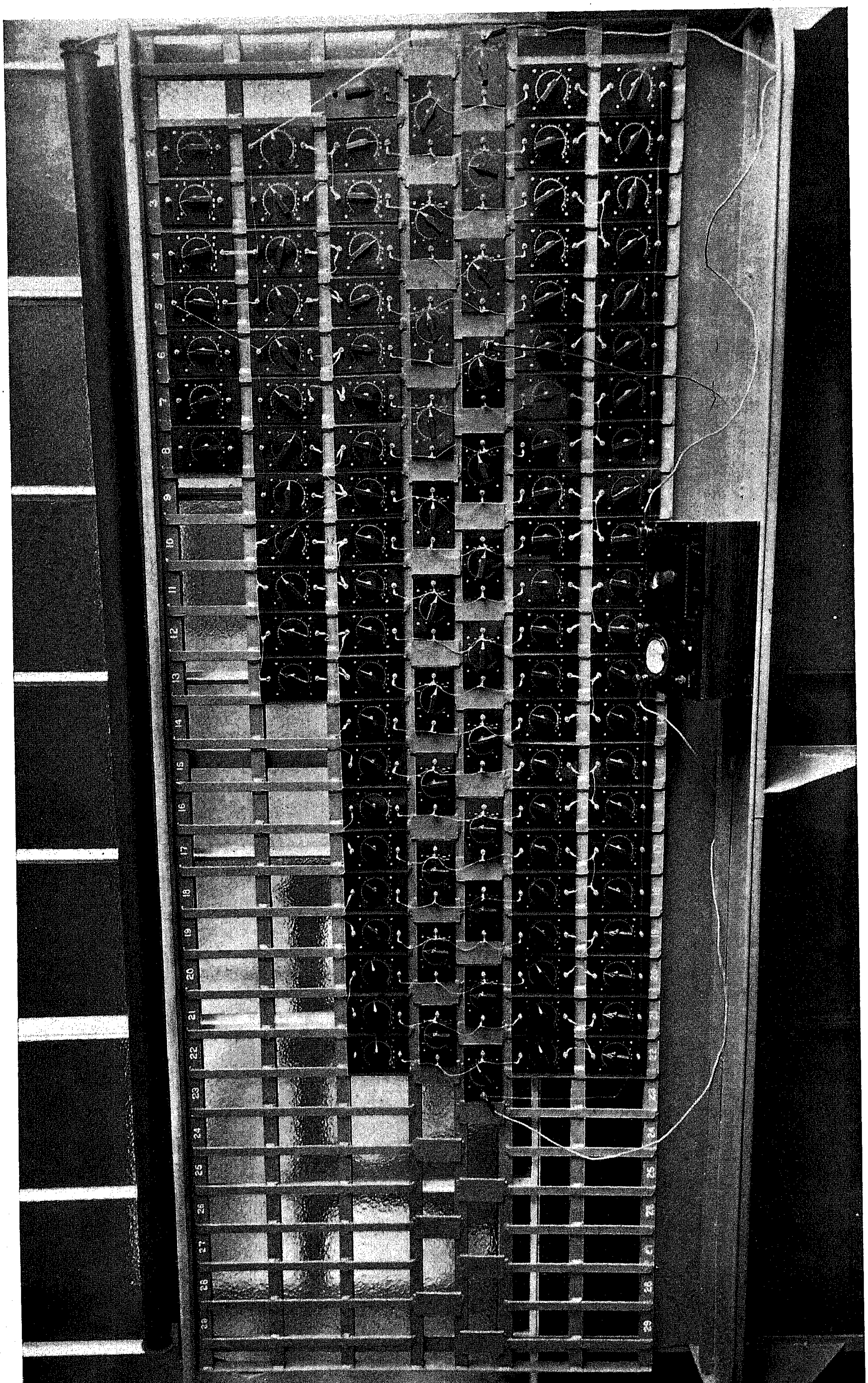


Fig. 25.—Calculating board for determination of initial impulse-voltage distribution in transformer windings.

causing the wave to be chopped, the applied voltage was not completely reduced to zero by the chop.

The oscillograms actually apply to the voltage across the first pair of coils at the line end of the winding, but the same principles hold good for other inter-coil voltages throughout the winding.

voltages produced by chopping would tend to be still higher.

In any case, the efficacy of shielding is clear, for it not only reduces the original oscillations produced by the full wave, but also reduces those superimposed when the wave is chopped.

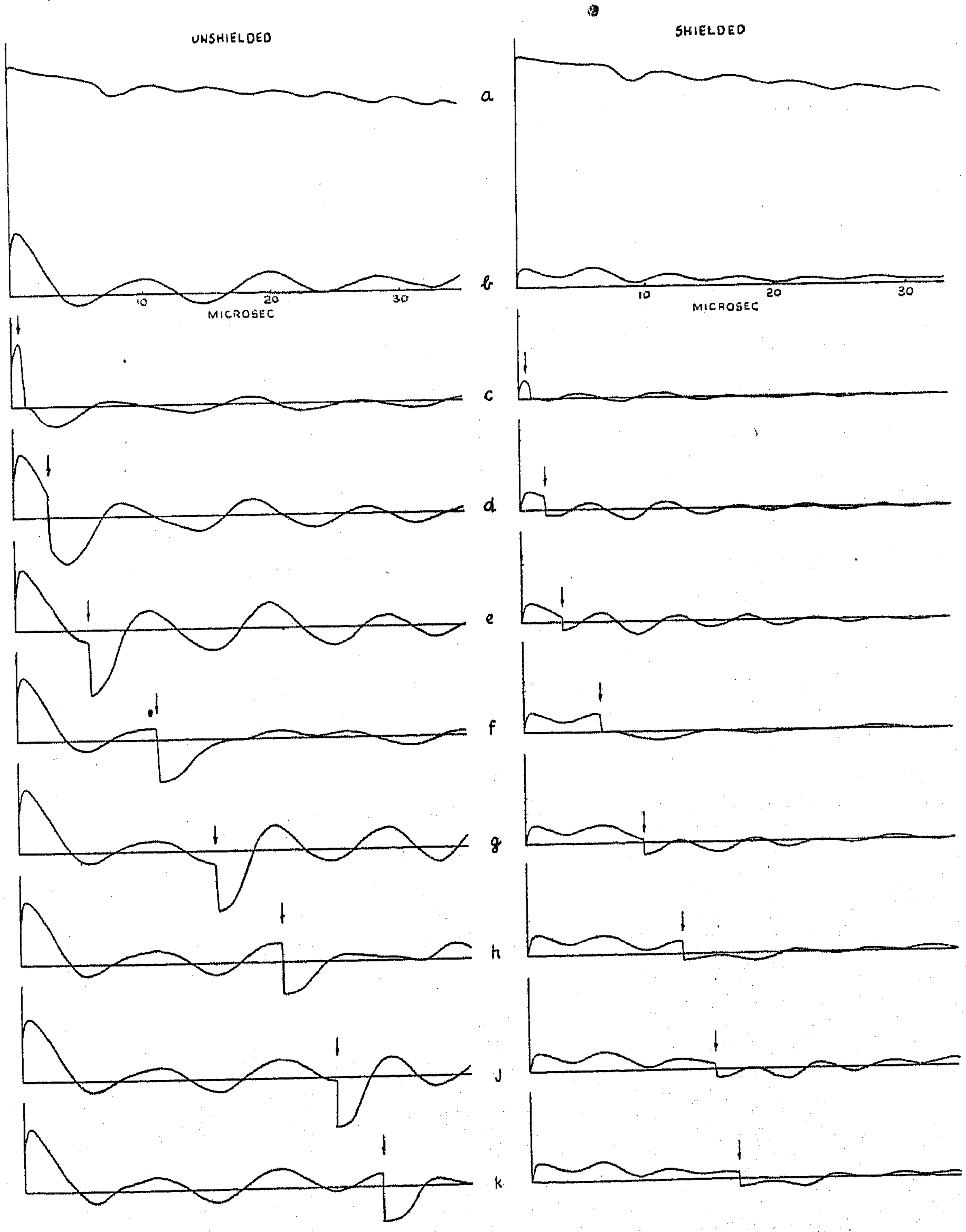


Fig. 18.—Effect of chopped impulse on inter-coil voltage transformer winding with and without shields.

Tests carried out with recurrent-surge oscillograph. Applied impulse wave 0·5/100 microsec.

a = wave form of applied impulse (full wave).
b = impulse voltage across first two coils at line end of winding due to full-wave applied impulse.
c to k = impulse voltage across same points due to applied impulse being chopped at instant indicated by the small vertical arrow in each case. Rate of chop slightly greater than front of wave.

In these tests, the rate of chopping was somewhat faster than the rate of rise on the wave front, though not greatly so. With a rate of chopping greatly in excess of the rate of wave-front rise, there would be a tendency for the superimposed oscillations to be of greater amplitude than those which would have been produced by the full wave, and in consequence the maximum internal

As a matter of interest, Fig. 19 has been included to illustrate the effects produced throughout a transformer winding when the applied impulse voltage is chopped on the front. These oscillograms show clearly that no excessive inter-coil voltages are produced by this means. The maximum voltage in each case is simply that determined by the initial distribution which obtains at the

instant of chopping. This is more or less completely neutralized by the chop, after which the voltage throughout the transformer remains substantially zero, no oscillations having had time to develop. Such small oscillations as are apparent in these oscillograms are partly due to the incompleteness of the chop, to which previous reference has been made. In each case the corresponding inter-coil voltage produced by the full-wave impulse has been included for the purpose of comparison. These tests were conducted on an unshielded winding, using the recurrent-surge oscillograph.

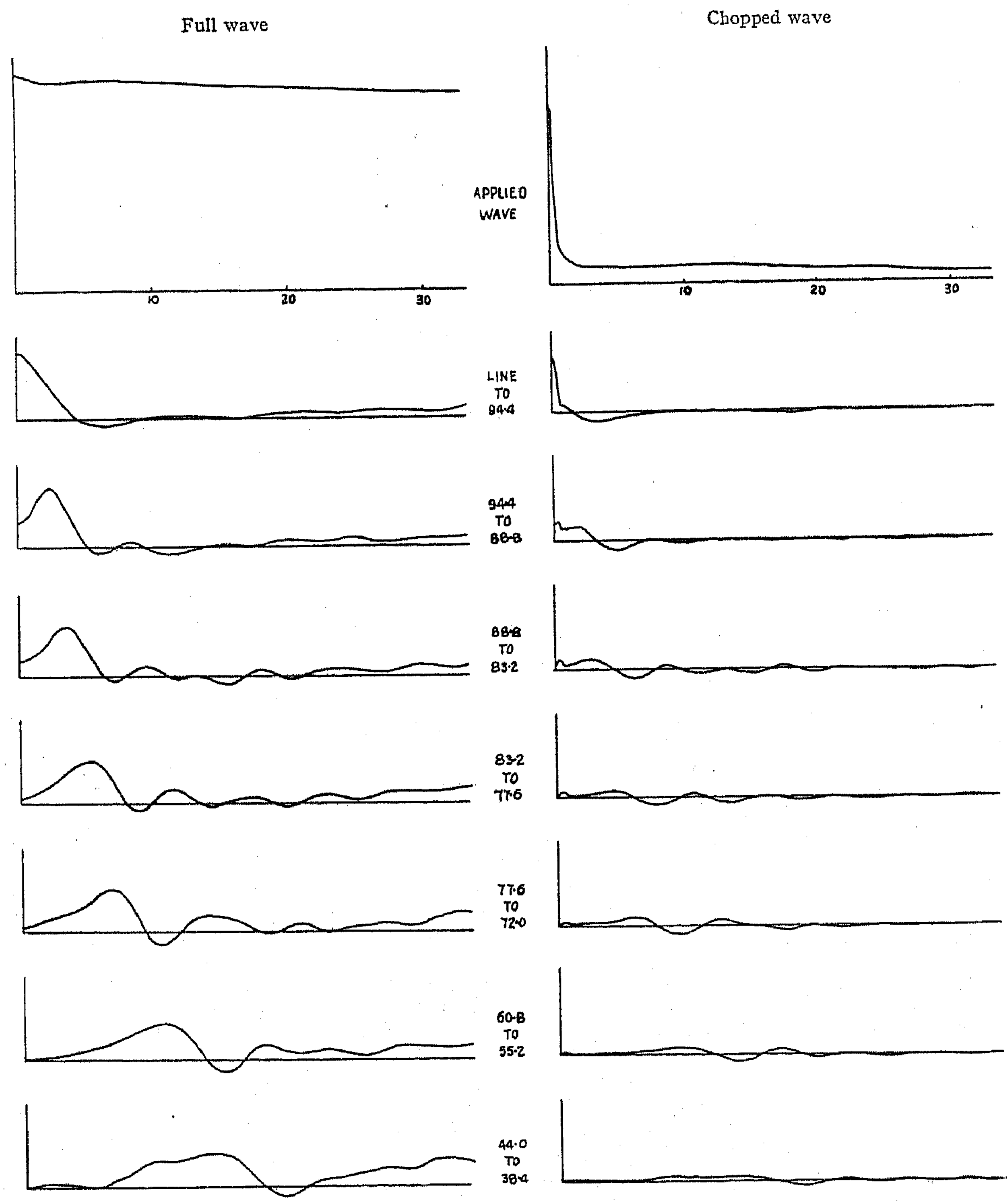


Fig. 19.—Inter-coil voltages in transformer winding produced by chopping on wave front of applied impulse.
Full-wave voltages included for comparison.
Tests carried out with recurrent-surge oscillograph.
Figures in centre column refer to percentage of winding from earthed end.

(7) INTER-TURN INSULATION STRESSES

In the foregoing discussion, attention has been directed mainly towards inter-coil (or axial) stresses, primarily because these appear to constitute the principal source of danger in transformers of normal design. Secondly, such voltages may be checked comparatively readily by means of the recurrent-surge oscillograph, provided that it is possible to obtain access to a few winding cross-over points for the purpose. The measurement of inter-turn voltages is a more difficult matter since the amplitudes are in general a good deal smaller than those of the inter-coil voltages, despite the effects of non-uniformity of distribution in the radial direction. Furthermore, it is difficult to bring out tappings from every turn without introducing distortion effects, and it is of course quite impracticable in the case of an actual production transformer. There are, however, several reasons why inter-turn stresses, when related to the amounts of insulation which can economically be provided in each case, are relatively less severe than inter-coil stresses.

In the first place, from purely theoretical considerations, it may be said that the maximum degree of non-

uniformity of voltage distribution in the radial direction will always be considerably less than that in the axial direction, except possibly in the case of exceptionally wide coils as sometimes used for interleaved windings. This is because the "series" capacitance from the outside to the inside of a coil radially is relatively very much higher than the corresponding quantity for the axial distribution, i.e. the total series capacitance from end to end of the whole winding. Also the "shunt" capacitance, which for the radial distribution may be regarded as the capacitance between adjacent coils, is relatively lower than the corresponding quantity for the axial distribution, i.e. the total capacitance of the whole winding to earth. The maximum initial gradient in the radial direction as obtained in this manner for a number of typical cases was found, for a rectangular impulse, to be of the general order of 3 times that corresponding to uniform distribution. The average inter-turn stress in a coil may be determined by dividing the maximum measured impulse voltage across the coil by the number of turns in the coil. The maximum inter-turn voltage is then 3 to 6 times this value. In practice, however, with actual wave-front times even of very short duration, there is a tendency for the radial gradients to be less severe than this on account of high-frequency oscillations within each coil, which can take place inside the wave-front time. A test made with a recurrent-surge oscillograph using a wave front of about 0·25 microsec. showed that the voltage across the first two turns of the line-end coil of an experimental coil stack was less than 3 times the average voltage per turn across the whole coil.

The radial shield, perhaps more usually known as the static end ring, has the function of distributing the initial electrostatic field more uniformly across the first coil at the line end of the winding, and thereby improving the radial voltage distribution. Such rings are invariably fitted to shielded windings and are a valuable adjunct to the axial shielding. It can be shown, also, that the radial shield also contributes to the improvement of the voltage distribution in the axial direction; though of course this is not its primary object.

A further point is that the inter-turn insulation is also a part of the insulation between coils, and thus the minimum amount to be used for any given conditions might to some extent be dictated by considerations of inter-coil stress. On this account the turn insulation provided on the shielded transformers referred to in this paper possesses a very liberal margin of safety over breakdown under impulse test conditions. This margin is several times greater than that of the inter-coil insulation, even when the inter-turn stresses are estimated on the basis of a pessimistically high value of radial non-uniformity. The inter-coil stresses may be predetermined approximately and may be checked fairly readily. The inter-turn stresses are not quite so readily determinable, and so it appears reasonable that the margin over breakdown for the inter-turn insulation should be somewhat greater than that for the inter-coil insulation, whilst the margin for the latter should be at least as great as, and preferably slightly greater than, that of the major insulation. The shielded winding provides a simple and economical means of attaining this ideal of a balanced insulation structure.

(8) INTER-LAYER INSULATION: BOBBIN-COIL WINDINGS

Another form of internal winding insulation is that which occurs between the layers of multi-layer, or bobbin, coils. The maximum impulse voltage-gradient within such a coil is not likely to be very greatly in excess of the average for the whole coil. This is because of the inherently good impulse-voltage distribution associated with the layer-type winding, of which each coil of a bobbin-coil winding is a miniature example. The impulse-voltage distribution within a single-section multi-layer coil is well illustrated by the test results recorded in Fig. 20. The coil tested was suitable for use as the h.v. winding of an 11-kV distribution transformer, except for the provision of numerous tappings for testing purposes. The curves show the initial impulse-voltage distribution to be almost linear, whether the

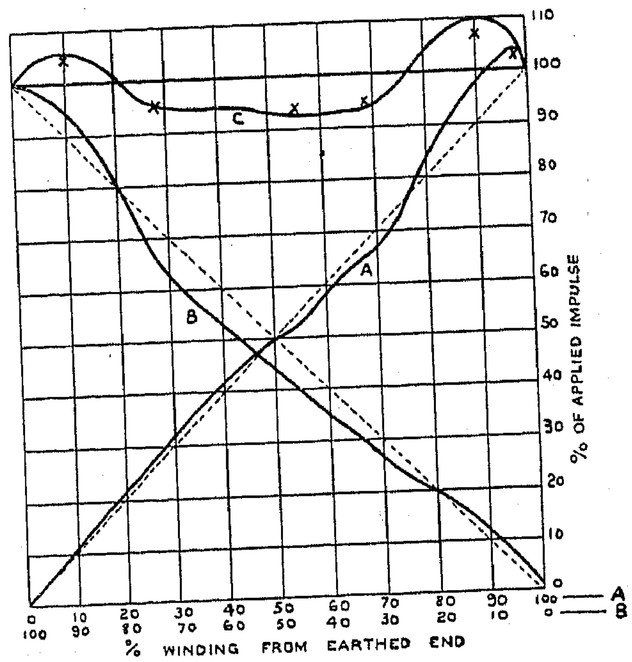


Fig. 20.—Experimental distribution-transformer winding with concentric cylindrical layers (tests in oil). Initial impulse-voltage distribution.

A. Impulse applied to outside end, inside earthed.
B. Impulse applied to inside end, outside earthed.
C. Graphical combination of Curves A and B.
Points marked X indicate initial voltages measured by the high-speed recurrent-surge oscillograph when impulses are applied to both ends of the winding simultaneously.

surge be applied to the inside or the outside of the coil. The initial voltage occasioned by the simultaneous application of equal impulses at both inside and outside ends of the winding is the combination of the two former curves, and varies but little from 100 % at all points in the winding. This means that under these conditions the voltage to earth at any point in the winding is substantially the same as the voltage of the applied impulse; this is illustrated by Fig. 21, and is in fact further evidence of the uniformity of the voltage distribution. The maximum voltage between layers, under the condition of an impulse applied to the outside end of the winding, the inside end being earthed, was found to be less than twice that corresponding to uniform distribution. The maximum voltage which could be found between tapping points within a layer, under the same conditions, was less than 4 times that corresponding to uniform distribution.

Hence, in a winding consisting of a number of multi-layer coils, the principal impulse stresses to be considered

are again those between coils. Here, also, shields can be successfully applied, and in point of fact some of the test results already described in this paper were obtained from windings of this type.

(9) INSULATION OF TAPPING BREAKS

Winding tappings are usually located on one or both sides of a break in the winding. This introduces a discontinuity into the winding, and as turns are tapped out, idle or overhanging portions of the winding are introduced adjacent to the break, these becoming greatest on the minimum tap connection. The impulse voltages appearing at such breaks are to some extent influenced by the possibility of free oscillation of the open end of the overhanging tap section of the winding. The voltage across

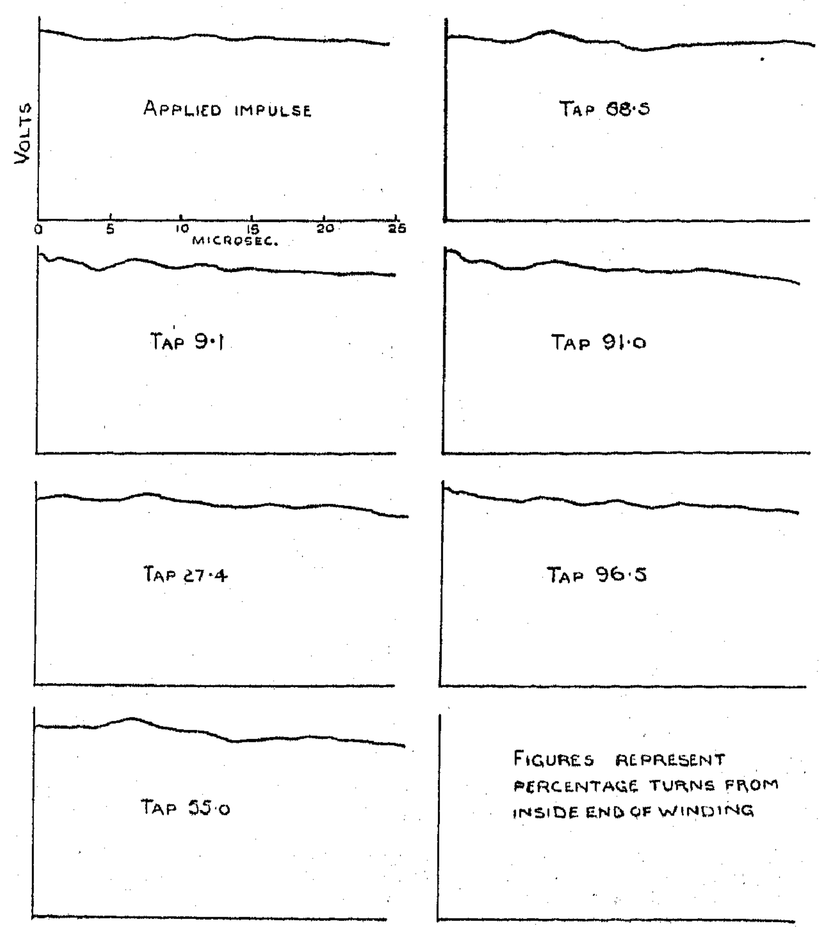


Fig. 21.—Experimental distribution-transformer winding with concentric cylindrical layers.

Test in oil. Impulse applied simultaneously to both ends. Voltages to earth.

a break appears also to depend upon the location of the tappings relative to the break, i.e. whether they are above, below, or on either side of the break. This is illustrated by the oscillograms reproduced in Fig. 22, which were obtained from tests on a typical high-voltage winding. Fig. 22(*a*) shows the voltage across the same tapping points, located at the same position as in the other cases, but with no break in the winding. The conditions giving rise to maximum break voltage in these tests are seen to be associated with the tapping arrangements shown in Figs. 22(*c*) and 22(*d*), though this voltage is not appreciably different from that shown in Fig. 22(*a*). It would thus appear that no excessively high voltage across a break is to be expected by virtue of the discontinuity, but at the same time it should be appreciated that the impulse voltage which does appear may easily be several times that corresponding to uniform voltage distribution. The insulation between the coils adjacent to a tapping break must therefore be designed accordingly. From tests on windings using numerous different

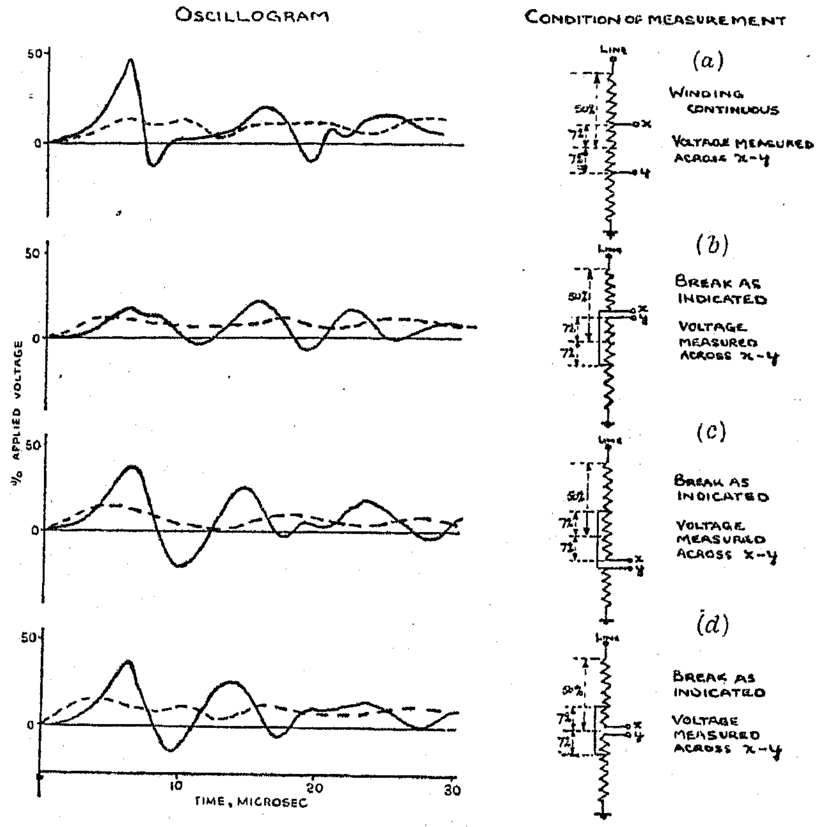


Fig. 22.—Tapping breaks: voltage appearing across typical tapping breaks on the application of a 0·5/100-microsec. impulse to the line end of the winding.

——— Winding unshielded.
– – – – Winding shielded.

In the diagrams on the right, the percentage turns in each case are expressed on basis of total turns in whole winding.

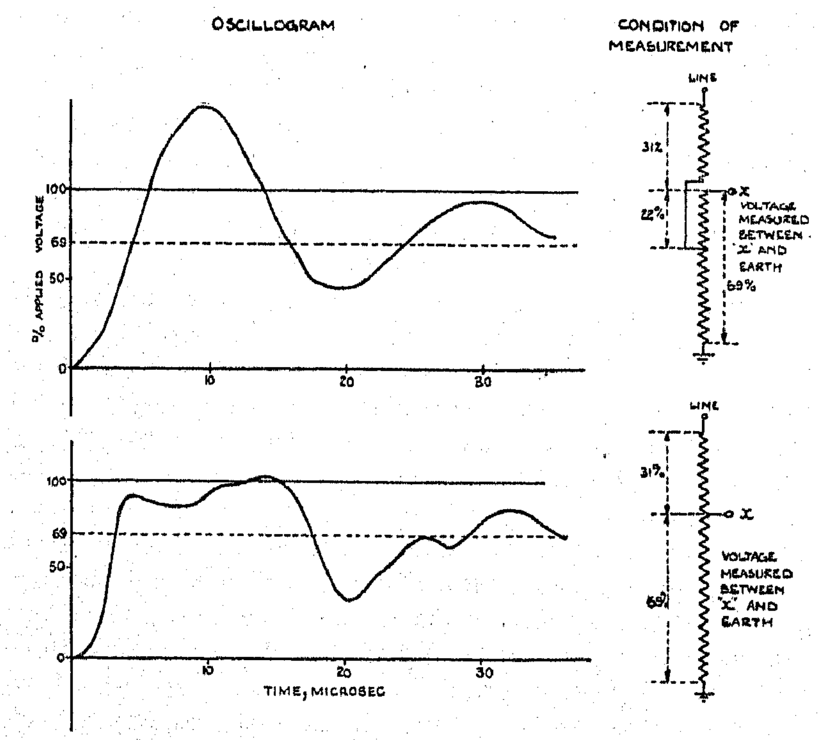


Fig. 23.—Tapping breaks: voltage to earth appearing at free end of overhanging tap section on application of 0·5/100-microsec. impulse to line end of winding.

In the diagrams on the right, the percentage turns in each case are expressed on basis of total turns in whole winding.

tapping ranges and with these tappings located at varying positions in the winding, data have been obtained from which the requirements for any given conditions may readily be determined.

The beneficial effects of shielding have been found to extend throughout the length of a winding so equipped, so that reduction in voltage stress is thereby obtainable in the case of tapping breaks. The dotted-line curves in Fig. 22 were obtained with the winding shielded, and have been included for the purpose of comparison. An incidental advantage in the reduction of the voltages between tappings and across tapping breaks by shielding is that reduced insulation stresses are imposed on connected tap-changing apparatus.

The voltage to earth at the free end of an overhanging tap section may reach quite high values in the case of large tapping ranges when located on the line side of the centre of the winding, the effect becoming rapidly more pronounced as the position of the tappings approaches the line. In exceptional cases, of course, additional insulation would be required between the low-voltage winding and the tap sections adjacent to the break. Insulation to earth on connected tap-changing apparatus must also be considered. In general, this condition is not likely to arise, but it is a possibility in connection with special designs. To illustrate the point, oscillograms are reproduced in Fig. 23 which were obtained during the course of numerous tests made for the purpose of accumulating design data.

(10) BALANCED INSULATION DESIGN AND CO-ORDINATION

In an ideal balanced insulation structure the strength would be everywhere commensurate with the corresponding stresses. It has been shown by the test results in Tables 2 and 3 that the maximum inter-coil impulse voltages in typical transformer windings may be of the order of 30 % to 70 % of the amplitude of the applied impulse, and therefore the corresponding insulation strength should be at least 30 % to 70 % of that of the major insulation. Now this amount of insulation between coils is not easily provided, and there is little doubt that very few high-voltage transformers of conventional design would approach this criterion. Furthermore, an increase in the amount of insulation between coils means a reduction of the inter-coil or series capacitance, with consequent increase of impulse-voltage stress, which to some extent tends to neutralize the benefit of the additional insulation. It would appear that it would be extremely difficult, if not impossible, to obtain the requisite increase in inter-coil safety factor by the use of increased insulation alone. The application of shields as described in this paper will reduce the stresses mentioned above to the order of 15 % to 25 % of the applied impulse voltage, and the insulation designed to co-ordinate with the shielding is sufficient to withstand these reduced stresses, with at least the same margin as that for the major insulation. In the case of exceptionally high voltages, the stresses should be reduced still further, and for this purpose more complete shielding is used. The degree of shielding used for any voltage depends upon securing an economic balance between the stresses and the insulation provided.

The shielded winding therefore makes possible an economical design in which it can be ensured that inter-coil failure under impulse conditions will not occur before major insulation breakdown. Inter-turn insulation stresses are inherently less than inter-coil stresses, and are also reduced by the action of the shields, so that the requisite amount of insulation is easily provided. It is thus possible to secure a higher safety factor against inter-turn breakdown than in the case of inter-coil or major insulation. This is desirable, since the inter-turn stresses cannot be predetermined with as much certainty as the major-insulation stresses.

With a transformer of balanced insulation design, it is known that the internal strength is greater than, or at least as great as, the major-insulation strength. Hence it becomes possible to use the latter as a criterion when establishing the insulation level of the transformer for co-ordination purposes. This simplifies the problem considerably, since the major-insulation impulse strength of a shielded winding depends only upon the amplitude of the applied voltage, and the internal stresses are taken care of in the design on the basis of rectangular wave-front. It is then only necessary to ensure that, under service conditions, the maximum amplitude of surge voltages reaching the transformer terminals is below the impulse test level of the transformer. In cases where lightning is frequent, it would be desirable to limit the surge voltage at the transformer terminals to not more than, say, 80 % of the impulse test level, to give additional margin against the cumulative effect of repeated impulses.

Various well-known protective measures are available for the purpose of this limitation of amplitude, and in the author's opinion the best of these is the surge diverter or lightning arrester, preferably of the type utilizing a voltage-dependent resistance material. The advantages of the latter are that the surge voltage can be held down to a value well below the impulse test level of the transformer, thus affording an additional margin of safety; and that, after the discharge of the surge current, the valve-like action of the device prevents the flow of power-frequency current.

The use of surge-limitation gaps is possible where economic or other considerations may prohibit the use of surge diverters, but there are limiting features such as, for example, the difference in the voltage/time characteristics of gaps and transformer insulation, and a discussion of these is perhaps outside the scope of this paper. Suffice it to say that with adequate direct-stroke protection and suitable amplitude-limitation devices, a shielded-winding transformer possesses a very high degree of immunity from breakdown due to lightning, to which no better testimony could be given than the unbroken service record of several million kVA of such transformers which have been operating successfully for many years.

(11) ACKNOWLEDGMENTS

The author wishes to express his indebtedness to the directors of the British Thomson-Houston Co., Ltd., for facilities to carry out the work described and for their permission to publish this paper, and to Mr. H. S. Holbrook, chief transformer engineer of that Company, for encouragement and advice throughout its preparation.

Finally, he wishes to express appreciation of having had the opportunity of interchange of views with Mr. K. K. Palueff and Mr. J. R. Meador of the General Electric Co., U.S.A., and of the valuable assistance

received from a number of his colleagues, in particular Messrs. K. J. R. Wilkinson and G. W. Carter of the B.T.H. Research Laboratory.

BIBLIOGRAPHY

Complete bibliographies covering papers and works dealing with surge phenomena in transformers were included in two recent Institution papers [Items (1) and (2) below]. It is therefore not considered necessary to repeat all such references, and the short list below is accordingly restricted to those works to which direct reference is made in this paper.

(1) T. E. Allibone, D. B. McKenzie and F. R. Perry: "The Effects of Impulse Voltages on Transformer Windings," *Journal I.E.E.*, 1937, **80**, p. 117.

(2) J. L. Miller and J. M. Thompson: "The Surge Protection of Power Transformers," *ibid.*, 1939, **84**, p. 187.

(3) Edison Electric Institute: Technical Report No. 2J–6 (October, 1934).

(4) L. F. Blume: "Transformer Engineering" (Chapman and Hall, London, 1938).

(5) K. J. R. Wilkinson: "Recurrent-surge Oscillographs, and their Application to Short-time Transient Phenomena," *Journal I.E.E.*, 1938, **83**, 663.

(6) L. V. Bewley: "Travelling Waves on Transmission Systems" (J. Wiley, New York, 1933).

(7) British Patent No. 491845—1938.

APPENDIX 1

Method of Calculating Capacitance Values for "Non-resonating" Shields

Considering the simplest case of uniform inter-coil capacitance throughout the winding, in order to secure linear initial voltage distribution between coils the series capacitance current flowing axially from one end of the winding to the other must be constant. This is ensured if the capacitance current to earth at any point in the winding is supplied by the shield. Hence, if $x =$ percentage turns from earth to mid-point of any coil in the winding; $C_1 =$ capacitance between shield and mid-point of the coil; $C_2 =$ capacitance between mid-point of the coil and earth; and E_x, $E =$ voltages at x and at line respectively; then

$$\omega C_2 \frac{xE}{100} = \omega C_1 E\left(\frac{100 - x}{100}\right)$$

whence

$$C_1 = C_2 \frac{x}{100 - x} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Theoretically, a non-resonating winding could be made with uniform inter-turn and inter-coil insulation throughout. For various reasons it has so far not been found desirable to take full advantage of this, and in consequence some departure from absolute linearity of initial impulse voltage is to be expected, but the errors associated with the use of the above formula in such cases do not appear to be great. The actual distribution could no doubt be determined by trial and error by the use of some such general formula as that given by equation (1) on page 308 of the book "Travelling Waves on Transmission Systems" by L. V. Bewley,[6] or can more simply be determined by means of a calculating board.

APPENDIX 2

Calculation of Shield Capacitance Values for Sinusoidal Initial Voltage Distribution

To obtain an initial impulse-voltage distribution having sinusoidal deviation from the uniform distribution, the requisite shield-capacitance values may be calculated approximately in the same manner as for linear shielding. From the desired curve of initial voltage let the percentage voltage to earth at the mid-point of any coil in the winding be e. Then, using the same symbols as for equation (1),

$$C_1 = C_2 \frac{e}{100 - e} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Actually there is a slight inaccuracy here due to the small difference existing in the voltage gradient between the coil under consideration and the adjacent coils above and below it respectively. It should be noted that, with sinusoidal shielding, the gradient is uniform at the centre of the winding, becoming greater towards the line end and lower towards the earthed end of the winding. This varying gradient throughout the winding, in contrast with the uniform gradient in the non-resonating design, demands a corresponding variation in the series-capacitance currents from coil to coil (assuming uniform series capacitance). Thus a small proportion of the shunt capacitance current for any coil must be supplied from the winding instead of coming entirely from the shield, and it is from this effect that the small inaccuracy in the above formula arises.

Comparison between the distribution curve obtained by the use of equation (2) and that obtained by means of the calculating board shows, however, that the errors associated with the use of this formula are but small in their effect. The maximum voltage-gradient with this type of shielding is given by

$$\frac{dV}{dx} = 1 + \frac{A\pi}{100} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $A =$ amplitude of sinusoidal deviation curve.

Theoretically, with an applied impulse having a rectangular tail, and neglecting damping, the above maximum gradient is transferred from the line to the neutral end of the winding at every half-cycle of fundamental frequency, whilst at every quarter-cycle from the start the voltage distribution throughout the winding is uniform. In other words, no internal gradients can occur during oscillation worse than the maximum initial value given by equation (3).

APPENDIX 3

Determination of Shield Capacitance Values for Simplified (Sub-divided) Shielding

This is most conveniently done by means of a calculating board, such as that shown in Fig. 25 (Plate 4). The essential capacitance values for the transformer winding are calculated from the transformer design, based on the use of the liquid dielectric medium actually

employed in the transformer (usually oil). To the calculating-board equivalent network composed of these values, elements representing the shields are suitably connected and adjusted so as to give an optimum curve of initial impulse-voltage distribution. The actual shields are then designed so as to have the capacitance values thus determined.

It is essential to ensure that the initial voltage distribution is a smooth continuous curve, for it is quite possible to obtain with incorrect shielding a point of discontinuity in gradient where the shields terminate. This has the effect of transferring the point of maximum stress from the line end to a point lower down in the winding, where the insulation may be less able to withstand it. Such an occurrence is avoided by careful grading of the shield capacitances, the values of which are readily obtained by the use of the calculating board.

The initial voltage distribution determined by the calculating-board method is based upon its being purely capacitive, i.e. as produced by a rectangular-fronted voltage wave. The calculations are thus based upon the worst conditions which could possibly occur, though in actual practice it is likely that absolutely sheer wave-fronts will be but rarely, if ever, encountered. The effect of some degree of slope in the wave front of the applied voltage would be towards a reduction in the initial voltage-gradient as compared with that due to a wave of vertical front.

As a general rule, it is obviously more convenient to carry out impulse-voltage distribution tests on transformer windings in air rather than in oil. By retaining the same shield arrangement, but modifying all affected capacitance network values, the effect of the change from liquid to air dielectric can readily be determined by the calculating board. Thus a direct comparison between test and calculation can be made, and the stresses for the transformer when oil-immersed may be deduced from the one test and the two sets of calculations.

As an illustration of the agreement between the initial

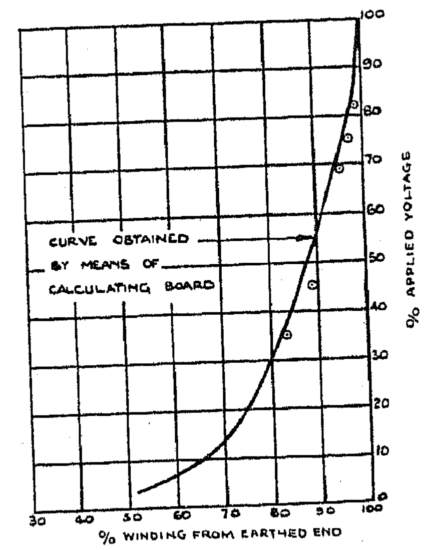


Fig. 24.—Shielded winding: initial impulse-voltage distribution. Comparison between estimate and test, for winding in oil. Shields connected.

Ringed points represent results obtained using a 70-kV impulse and a high-voltage cathode-ray oscillograph.

impulse-voltage distribution in a shielded winding as estimated by means of the calculating board, and the results of cathode-ray oscillograph tests, Fig. 24 has been included. It shows the estimated curve for the winding in oil, together with test results taken from the impulse tests in oil on the transformer referred to in Section (6)(c).

DISCUSSION BEFORE THE INSTITUTION, 22ND FEBRUARY, 1940

Mr. C. W. Marshall: My comments on this paper will be made from the standpoint of users of what the author terms medium-voltage transformers.

Some hundreds of these transformers were built to the empirical specifications customary in all countries in the past, the tests being an induced-voltage test of 2·73 times normal voltage at suitably increased frequency, a 45-kV inter-winding test, and a series of inter-turn insulation tests on sample coils. These results of inter-turn insulation tests on five different makes of such transformers (see Table A) are strikingly indicative of the need for rationalization in transformer insulation design. The ratio of maximum to minimum breakdown voltage on the 132-kV grade is almost 2 to 1; on the 44-kV grade it is over 2 to 1; and on the 26·4-kV grade it is 2·6 to 1. These figures indicate a very wide diversity of opinion between transformer designers as to what is necessary and sufficient to make a transformer safe.

On transformers of all voltages up to 132 kV, and particularly 33 kV, 66 kV and 132 kV, there are occasional failures due to over-voltages, the proportion being something less than 1 % per annum; but the elimination even of that 1 % is very desirable. It is clear from past experience that there is much to be done in the way of producing transformers of given characteristics with the minimum expenditure of material. So far as the switching surges

Table A

"INTER-TURN INSULATION" TEST RESULTS (kV)

Manufacturer	132-kV grade*	44-kV grade*	26·4-kV grade*
A	204 175	97·5 57·5	97·5 37·5
B	116 108	71 71	42·5 42·5
C	200 159	70 54·5	42 42
D	151 120	114·3 69	52·1 50·2
E	194 109	108 71	54 51

* The column headings indicate the a.c. test which the inter-turn insulation is designed to withstand for a period of 10 sec.

The test figures given are the kilovolts at which the insulation broke down when the applied voltage was steadily increased after successful completion of the "10 sec." test. For each manufacturer, maximum and minimum breakdown voltages are given.

are concerned, it is a matter of considerable difficulty to define these in terms of volts and microseconds; but what we do know is that when we use a 26-in. rod-gap on a 132-kV system we begin to get occasional flashovers, and therefore if we get much below 26 in. we are liable to have fairly numerous switching flashovers, which have a bad effect on operation. So far as I am aware, however, no case has occurred of failure of a transformer due to switching surges.

Lightning remains the one serious enemy, and it has been tackled by the E.R.A. on behalf of the suppliers and manufacturers in this country, with the assistance of the Central Electricity Board. Investigations have been made into the characteristics of lightning and of the surges which can be impressed by it on terminal apparatus, as well as into the characteristics of the insulating material.

The most clamant need from the users' side is to know the impulse voltages that transformers can safely withstand, and it would be of interest if the author would give some data of this sort, in terms of, say, rod-gap settings, regarding 132-kV transformers made by his company.

Mr. E. T. Norris: Up to the time of the large improvement in the surge strength of power-transformer windings that has recently taken place and of which the paper gives examples, the surge strength of the general run of power transformers had changed very little in a period of some 20 years. The sudden change which has just occurred is all the more striking because the principles of surge reactions in a winding which are the foundation of this paper—that is, the initial distribution due to capacitances between turns and coils, the subsequent oscillations, and the final or dying-away distribution—were all described in full detail in 1915.* Again, shields similar to those shown by the author (apart from details of construction) were produced by Haefely, of Basle, in 1918.† (A typical example can be seen in the 1 000 000-volt transformers at the National Physical Laboratory.) The full non-resonating principle referred to in the paper was published in 1921. Almost every conceivable combination of shields is in principle the subject of an expired patent. Yet, in spite of all this, the extensive practical application of these principles is relatively recent. I think that the reason is that for many years they were known and understood only qualitatively. It is only since the invention and development of the surge generator and high-speed cathode-ray oscillograph that detailed studies of inter-coil and inter-turn stresses have been possible, permitting the determination of quantitative formulae whereby constructions such as the author describes may be accurately designed.

There are three methods of improving the surge electric strength of a transformer; the ideal one is so to design the winding that an incoming surge is naturally distributed uniformly through it. This principle was applied in connection with the non-resonating winding of a 500 000-volt transformer which was designed and built in this country in 1923. Unfortunately thermal and mechanical considerations render it generally impracticable to employ such windings on power transformers. The second method is to improve the initial voltage distribution by means of shields, as described by the author. The third method is based on the theory that uniform distribution of the voltage is not essential; what is essential is a uniform distribution of the stress, with the same efficiency of utilization of the insulation throughout the winding. The voltage distribution is largely determined by the insulation between turns and coils, and this same insulation, of course, determines the electric strength. It has been found possible to co-ordinate these values so that the surge coil and transformer voltages, whilst not necessarily uniform throughout the winding, are in proportion to the insulation strength at every point and result in substantially uniform stresses. The use of the insulation actually providing the electric strength to control the corresponding electrical stresses has suggested the term "stress-control" for this type of design.

The author mentions that it is quite practicable to obtain increases in strength of 2 to 5 times, and that is the kind of increase that we have found possible with this design. I think it would be possible, as probably the author will agree, to go even further, but I am doubtful whether this is in general necessary because failures due to lightning are not frequent with existing designs, and these increases will provide a degree of immunity probably sufficient for normal operating conditions.

In regard to the surge strength of transformers, I agree with the author's calculations and measurements in considering that the chief difficulty relates to inter-coil stresses, and that inter-turn stresses due to the natural construction of coils in core-type concentric-winding disc-coil transformers seldom need consideration. Also, in testing a large number of such transformers to destruction I do not recall a single case of between-turns failure, thus confirming both theory and measurements. Yet such failures have indisputably been caused in service by lightning.

Dr. T. E. Allibone: Various methods have been advanced for reducing the concentration of stress in transformer windings when subjected to impulse voltages. The present paper concerns itself solely with one of those methods, namely the provision of shields around the winding to distribute more uniformly the electric stress throughout the whole winding.

The method advocated specially by the author, the so-called simplified shield, is strikingly neat: the material employed is almost identical with that of the secondary winding, it requires the same thermal treatment and oil impregnation, and even the technique of application of the shield conforms to standard transformer practice. The shield is presumably fairly cheap, except for the investigational work necessary before any new design can be formulated.

My concern, however, is for the degree of improvement effected by the two types of shield; is it sufficient to justify the introduction of the shields? First, consider the so-called "non-resonating" design described on page 430, the theory of which is set out in Appendix 1. Suppose a winding is composed of 25 coils: then the capacitance between the shield and the first coil must be 24 times as large as the capacitance of that coil to earth;

* J. M. Weed: "Abnormal Voltages in Transformers," *Transactions of the American I.E.E.*, 1915, **34**, p. 2197; also K. W. Wagner: "Progress of Waves in Windings," *Elektrotechnik und Maschinenbau*, 1915, **33**, pp. 89 and 105.

† British Patent Specification No. 170547.

the capacitance between the shield and the second coil must be 12 times as large as the capacitance of the second coil to earth; and so on. It is difficult to see how such large values of capacitance can be added by the method described in Fig. 3 and illustrated in Figs. 4 and 6, and yet if these values are not achieved the winding will not be "non-resonating," and it will therefore not be practicable to economize insulation as much as it would be if the winding were truly "non-resonating." Can the author indicate to what degree compromise has to take place?

Secondly, consider the simplified design of shielding. This does not of course pretend to provide the same degree of additional capacitance as is provided by the former design, and so does not prevent stress concentration at the ends of the winding. Although inter-turn and inter-coil stresses are reduced the axial stress on the major insulation starting from the line coil is not significantly lowered. Consider, for example, the stress across the first 20 % of the winding from the line terminal as given in Figs. 11 and 15: in Fig. 11 this stress is reduced from 80 % to 65 %, in Fig. 15 the reduction is from 86 % to 72 %, so that the tendency for breakdown of the major insulation to occur axially from the line coil would not be greatly reduced in this simplified design of shielded winding.

The author is well aware of the controversy with regard to the provision of reinforcement of insulation on the end turns of a winding. When the simplified form of shield is employed, is it possible to eliminate entirely reinforcement of end turns?

On page 430 he mentions the use of capacitors placed across pairs of coils: it is clear that if external capacitors are used the added capacitance per coil can be far greater than that given by any form of shield—either the "non-resonating" shield or the simplified shield. Has the author given any thought to the feasibility of constructing windings with such capacitors? I tend to favour such construction so as to be able to eliminate entirely reinforcement of end-turn insulation.

The author does not mention actual tests to destruction on models made to the designs he advances in this paper. I recognize that such tests are expensive, but they are after all the final arbiter of the success of the various designs, and I should welcome impulse-voltage breakdown test data on identical designs with and without shields.

My final point concerns transference of surges to the l.v. circuit. The simplified shielding is most advantageous in removing the higher harmonics of the modes of oscillation of the h.v. winding. The fundamental mode is not greatly reduced in amplitude, and therefore the transferred surge (that component which is transferred magnetically and not electrostatically) will not be appreciably reduced. Does not the author consider that more extensive shielding is warranted so that the low-voltage circuit may benefit as well as the high-voltage circuit?

Dr. J. L. Miller: In the past there has been considerable controversy—I myself have been engaged in some of it—about the relative importance of axial and major insulation stresses under surge conditions, and it is therefore with great interest that I see the author taking some pains to point out that from his knowledge the axial and not the major insulation is the danger point under surge conditions. To use the author's own words (page 428), "the established standards of high-voltage test have resulted in major insulation which has proved itself generally adequate by satisfactory service records even in districts subject to severe lightning." To me this is a most important statement, and fully supports the experience, figures and test results my colleagues and I have been citing for a long time now.

Actually, an ordinary transformer, when subjected to travelling waves, has, in round figures, a safety factor of 2 to 1 or more in the major insulation direction and a factor of weakness of about 1·5 to 1 in the axial direction. Had this not been true generally there would have been no need some years ago for the development of the non-resonating transformer, since all that such a design effects (as the author also very truly states) is to make possible an economical design in which it can be ensured that inter-coil failure under impulse conditions will not occur before major insulation breakdown.

This proper appreciation of the manner in which lightning breakdowns occur in transformers suggests methods for the alleviation of the trouble. The method described in the paper aims first at making the strength of the axial insulation equal to or greater than that of the major insulation—the latter then correctly establishing the travelling-wave insulation level of the transformer—by designing for an initial distribution as near linearity as possible. Then not only will the major insulation safely withstand surges the amplitudes of which do not exceed the insulation level, but the axial insulation will also now withstand the steepest fronts or chopped tails of the same surges.

In practice, however, the level will often be exceeded, and in fact voltages up to 15–20 times the operating voltage or more may occur. Thus in such cases in order to prevent breakdown of major or axial insulation—and it must be kept in mind that the major insulation stresses are unaffected by the employment of a non-resonating type of design—the author would add a safety valve to the system set at a level a little below the safe level of the transformer. As the author points out, plain rod-gaps or expulsion gaps will not suffice to limit the surge voltage sufficiently, because of their high values of impulse ratio for short times to breakdown. Therefore, the author requires the installation of arresters, which in turn demand the use of good overhead shielding extending outwards from the substation for about 3 span-lengths.

The foregoing describes in outline the principles involved when a non-resonating type of transformer winding is used, and no criticisms will be levelled by me against this method of minimizing the risk of breakdown by lightning. But I should like to draw attention to the fact that there are other ways of increasing the axial insulation strength under surge conditions. One of these, the method of surge-stress control, has been referred to by Mr. Norris. Another involves the use of wave flatteners.

I refer in particular to the surge absorber, which as far as travelling waves are concerned effectually removes the disparity between the axial and major insulation stresses in a transformer winding by sloping off the wave fronts or tails. When the travelling-wave level is exceeded, the surge absorber in conjunction with a simple rod-gap or

expulsion gap, despite the high impulse ratio of these gaps, will limit the transformer surge voltage to a value which does not exceed the maximum possible travelling-wave value. Thus, whatever the conditions, the transformer will be fully protected; and, in fact, the surge absorber acts as an effective insulation co-ordinator, not only always ensuring ample security for the axial insulation but also providing protection for the major insulation just when it is wanted. In any particular case, of course, the decision as to whether surge absorbers be employed, or whether the alternative methods of non-resonating or surge stress-control designing be adopted, will depend on conditions and economics. But in any case one must not lose sight of the co-ordinating properties of the surge absorber under the impact of direct strokes.

On page 429 the author refers to end-turn insulation, pointing out that the reduction in the series capacitance and in the number of turns per coil occurring when the end coils are reinforced produces increased voltage concentration which, to some extent, neutralizes the advantage of the higher electric strength obtained. I suggest, however, that the wording is not sufficiently explicit and may even create a wrong impression, since what really matters finally is the voltage gradient or volts per mil in the insulation and not the voltage itself. Thus a design not having any reinforcement will have both maximum voltage and maximum gradient at, or almost at, the line end. When the generally accepted amount of reinforcement is added the maximum voltage will still occur at the line end and may even be increased. The maximum gradient, however, will probably now occur elsewhere in the winding and may be greater than that previously obtained without the reinforcement. Actually, not only have we been able to demonstrate experimentally* that a large winding without reinforcement can be stronger axially than a similar winding with reinforcement, but we have also found that the position of maximum inter-coil stress, shown to exist in one particular case just below the reinforcement, agreed with the position of an inter-coil failure due to real lightning. It does not follow, however, that with the present-day standards of reinforcement the maximum stresses are always just below the reinforcement. They may, in fact, occur well down in the winding.

I am in full agreement with what the author says about the effect on the inter-coil stresses of chopping on the wave tail. I am not in agreement, however, with his cursory dismissal of the effect of chopping on the wave front. The impulse ratio of insulators and gaps increases rapidly with increasing rate of voltage-rise, so that flash-overs on the fronts of waves will not occur before the surge voltage has attained a value which, in the worst conditions, may be 20 or more times the operating voltage. Thus the tendency for a surge voltage chopped on the front to give smaller stresses than a voltage chopped on the back is nullified by the greater voltage amplitude. We have often found experimentally that, in windings having normal reinforcement, waves chopped on the back produce maximum axial gradients which are a little less in magnitude than those produced by waves (of appropriately greater amplitude) chopped on the front.

* J. L. Miller and J. M. Thomson: "The Surge Protection of Power Transformers," *Journal I.E.E.*, 1939, **84**, p. 187.

The matter is further complicated by the fact that in general the former maximum gradients occur somewhere near the beginning of the unreinforced sections while the latter occur at the line end of the winding. It is complications such as these that exclude the possibility of eliminating reinforcement in the future.

I agree with the author's remarks on inter-turn stresses. Our results have always so far shown us that in normal transformers having disc coils the voltage gradients in the inter-turn insulation are smaller than those in the inter-coil insulation. In fact, as an average, in windings of medium or large outputs, the maximum inter-turn gradients are of the order of 1/6th to 1/10th of the maximum inter-coil gradients. These findings, too, have always been cofirmed when testing transformers to destruction in the laboratory.

I would ask about the measure of agreement between the results obtained from the calculating board—a most excellent device—and the corresponding transformer winding for positions, say, 10 % to 15 % from the line end, when the initial voltage distribution departs from linearity. The board is used to examine the transient performance of transformers having only partial shielding, and will no doubt also be employed for normal transformers. In such cases, particularly in the latter, inter-coil stresses of considerable magnitude, existing at distances considerably removed from the line end, will occur sufficiently late in time to warrant the conclusion that the inductive elements of the winding are participating in their production. Yet the calculating board only simulates the capacitances. Perhaps the author would state from his experimental knowledge whether there is any difficulty here.

I agree with a great deal of what he says about bobbin-wound coils; they inherently have a good voltage distribution. Nevertheless, we have found cases where, with a number of bobbin-wound coils on the leg, the ratio of the voltage between two layers to that occurring with an average distribution across layers was, for certain positions in the winding, considerably greater than the figures given in the paper. The author, too, says nothing about the voltages between adjacent turns in a layer. We have found voltages very much greater than those occurring with a uniform distribution across turns. These voltages existed, however, somewhere in the reinforced layers where, in the low-voltage transformers to which this type of winding is applicable, the inter-turn insulation is so strong relatively that the danger of breakdown is not so great as might appear from a first consideration of the figures.

Dr. E. Billig: When reading Sections (2)(*a*) and (2)(*b*) I cannot help feeling that the author has in mind some kind of cumulative effect of the voltage stress on the insulation; for instance, when he states that an earth fault would be withstood by the insulation of a transformer for about a "10-hour period, not more than once in every 3 months"; or again, it would take about 10 000 switching surges "to make up a total period equivalent to the 1-minute insulation test." The author apparently has in mind some kind of process whereby the insulation slowly deteriorates with the time of application of the voltage in a cumulative way, something similar to the charring effect of overheating.

It is indeed of great practical importance to be able to predict the probable life of a transformer from the loading cycle and temperature, as, for instance, is demonstrated by Blume in his book on "Transformer Design." But I am afraid this cannot be done in the same way for voltage stress. The voltage/time characteristic, as expressed, for instance, in Peek's law, is only an expression for the limit of stability of the insulation material. At any one temperature the dielectric will pass a certain leakage current corresponding to its insulation resistance and give a certain dielectric loss. With a higher voltage that leakage current will rise. The higher loss will raise the temperature and this will lower the insulation resistance appreciably, which in turn will make for higher loss, and so on. It is now mainly a question of cooling whether the insulation will reach another point of equilibrium where the higher losses can be dissipated properly or whether it will become unstable and break down. The expression for that criterion is the law mentioned above. But surely if the higher voltage is not applied continuously the dielectric will have time to cool off and no cumulative effects can result: in other words, if a piece of apparatus is able to withstand a certain over-voltage several times without any damage it will do so again any number of times under the same condition.

It seems that most of the author's oscillograms have been obtained by applying surges to a high-voltage winding. Now it is quite interesting to know what would happen to any other winding—either on open-circuit or on load—on the same transformer core. I have had the opportunity of carrying out some experiments on that point recently. A recurrent-surge oscillograph was used, and the voltages on the secondary winding were investigated with the impulse applied to the primary of a single-phase transformer. It was found that the surge was transmitted to the secondary in the full turns ratio. Reflection interference-phenomena and free oscillations were found superimposed on the original wave. The load impedance has, of course, a great bearing on these phenomena.

All that may be quite interesting with an ordinary transformer, but it is of paramount importance in the case of a booster transformer, where a surge arriving from the line will be stepped up to the primary side of the booster corresponding to its turns ratio and be transmitted into the exciter transformer unless special precautions are taken. A complete investigation of this problem is now being carried out.

Turning to the practical side of the paper, it is important for the designer to know the voltage stresses which appear across any part of the winding. As the author points out, the most dangerous deviations from uniform voltage distribution in the classical design appear between coils, but these can be dealt with quite easily by reinforced insulation. I think the bad effect of that on the capacitance between coils has been rather exaggerated, because an increase in inter-coil insulation does not appreciably affect the capacitance between coils. There is generally an oil-gap in series with the solid insulation which will not be altered in size. Very rarely, if ever, has a properly designed high-voltage power transformer broken down between coils in service. The field of application of shielding may be larger for voltage transformers where the turns and coils cannot be so heavily insulated and where the addition of heavy insulation would indeed alter the capacitance appreciably.

I therefore rather doubt whether it is worth while interfering with the neat design of the modern power transformer by connecting large metallic shields to its live side. Even the provision of extra turns outside the main body of the winding, as illustrated in Fig. 8, must invariably interfere with the cooling and ultimately with the life of the transformer. It is just the most valuable vertical cooling surface on the outside which is covered up by the heavily insulated extra turns.

(*Communicated*) The conventional way of surge protection, employing a "condenser" or "static end-ring" connected to the live end of the winding, has been found most beneficial in practice. It will certainly protect the inter-turn insulation in the first coil, as all the turns are charged up to full potential immediately, i.e. the radial voltage distribution is almost perfect. In considering the initial axial voltage distribution it is sometimes overlooked that a surge rising to its peak in a microsecond will have travelled some hundred turns into the winding before the peak arrives at the transformer terminals. This should be borne in mind when considering the "initial" voltage distribution as governed by the capacitance values of the winding.

Mr. H. M. Lacey: There are three points in the paper to which I should like to refer.

The first is that all the distribution diagrams are drawn with the earthed end of the winding on the left and the line end on the right; these diagrams are usually drawn the other way round, and it would be better to follow the normal practice.

The second point concerns the calculating board. There are two main difficulties in making calculations of the kind described in the paper; the first is the complexity of the calculations, and the second is the difficulty of estimating the series capacitance. The calculating board ameliorates the first difficulty, but no mention is made of the method of overcoming the second.

Thirdly, with regard to the experiment described in Section (8) which purports to show that the distribution of voltage in a single multi-layer coil is uniform; if the coil is inserted in the transformer, it has to carry not only the currents due to its own capacitances, but also the capacitance currents which pass through that coil to all coils between it and the earthed end of the winding. In other words, testing the coil separately proves little.

Turning to the general question of protection of transformers, it is unfortunate that most papers which deal with this subject do not discuss its economic aspect. There are two main classes of protection: one consists in reducing the steepness of the front of the wave so as to improve the distribution, and the other in minimizing the peak voltage of the wave. The shielding method described in the present paper belongs to the first of these two classes. Mr. Marshall mentioned that failures due to lightning had not exceeded 1 %. Assuming the cost of repair to be one-third of the original cost of the transformer, and the rate of interest to be 5 %, it may be concluded that the justifiable cost of protection is limited to $6\frac{2}{3}$ % of the original cost of the transformer,

provided that the transformer has an infinite life. If it has a life of only 20 years, the justifiable cost is reduced to $4\frac{1}{2}$ %. A factor which tends to increase this figure is what may be termed "goodwill," i.e. the consideration that interruptions to supply are undesirable, but probably in no case in this country could an expenditure of more than 10 % of the original cost of the transformer be justified. All these figures are based on the assumption that the protection provided is perfect, an assumption which applies only if (*a*) the peak voltage of the wave is reduced to a value which the major insulation of the transformer can withstand, and (*b*) precautions are taken to ensure that the wave fronts are such that the end-turn insulation is not overstressed.

Prof. C. L. Fortescue: I should like to make a protest against the terminology which is growing up round this subject. The term "resonating transformer" is a misnomer, as it is not intended to refer to resonance in the ordinary sense of that word. The term may possibly be interpreted as resonance on the part of various circuits within the transformer to the infinite series of terms in the unit function, but this is not the usual meaning of it. Secondly, I object to the word "shielding." This does not refer to a shield but to a means of adding to certain capacitances. When we apply the same process to a string of insulators we speak of "equalization," and I venture to suggest that some term of that kind would be more appropriate than the word "shielding."

Mr. J. B. Hansell (*communicated*): It is clear from the paper that the type of shield described reduces the voltage gradient in the winding when a steep-fronted voltage wave strikes the terminal. In order, however, to justify the application of such a shield to a transformer, the author must show that a transformer so fitted is better economically than one designed in the usual manner, with the insulation between the end turns increased so that it will withstand the transient voltage.

On page 441 he states that a transformer with a shielded winding possesses a very high degree of immunity from breakdown due to lightning. The service records of large and medium-size transformers without shields, produced by reputable firms, show similar immunity. There is, however, a strong case for the shielded design if it can be shown that the same immunity can be obtained more economically than with the unshielded design.

Table 2 gives numerical comparisons between internal voltages obtained on a transformer before and after fitting shields. The voltage distribution in the winding without the shield seems to be very bad, and I should be glad if the author would state what was the ratio of the turns in the end section to the turns in a section in the body of the winding, and also what was the distance from copper to copper between the two end sections as compared with the corresponding distance between sections in the body of the winding.

In regard to the shield itself, the non-resonating shield illustrated in Figs. 3, 4 and 6 appears to require insulating very heavily from the winding; it would seem, too, that it may be rather difficult to bring out tappings from the windings and that, although the shield may be effective in reducing the transient voltages between sections to a minimum, it may introduce weaknesses in other directions. The simplified shield is much more attractive than the non-resonating type, and although it is a compromise it appears to be sufficiently effective.

I should like to ask the author whether he has applied impulse voltages simultaneously to both ends of a delta-connected winding fitted with simplified shielding, and, if so, what rise in voltage can be expected at the middle of the winding under this condition, as compared with the voltage obtained before shielding.

Dr. Allibone favours the application of independent capacitors across portions of the winding, and Table B shows the improvement in maximum amplitudes of inter-coil voltages under impulse conditions which have been obtained on a transformer winding when capacitors were fitted. The transformer in question had 12 bobbin-wound coils, and capacitors were connected across the first and last 3 coils. A 1/50 impulse-voltage wave was applied to coil No. 1, and coil No. 12 was earthed. If comparison is made with Table 2 of the paper it will be seen that the proportional improvement was about the same as that obtained with the modified shield.

Table B

Coil No.	Percentage of impulse voltage applied to the whole winding		Percentage volts ÷ percentage turns	
	With capacitors	Without Capacitors	With capacitors	Without capacitors
1	19	54	2·3	6·5
2	16	41	1·93	4·95
3	17	31	2·05	3·75
4	22	26	2·65	3·13
5	21	24	2·53	2·9
6–12	Less than 12 % across each coil	Less than 26 % across each coil	Less than 1·45	Less than 3·15

Condensers were only fitted to three coils at each end of the coil stack, as it was only desired to obtain a certain degree of improvement. A greater degree could have been obtained by increasing the number and size of condensers.

In Section (2) the author states that a transformer tested at twice line voltage for 1 minute can be operated with one line earthed for a period of 10 hours in every 3 months. It would be interesting to know how this deduction was made.

Mr. J. Whitcher (*communicated*): The method of shielding is the only direct way of tackling the more intricate problems of impulse-voltage risks in a transformer winding, and it is important to have it scientifically investigated and discussed in a practical way. End shielding of the stacks of coils in more or less crude fashion has been of immense service to transformer technique in the past; what has been so irritating has been the timid way in which the principle has been applied. The idea of controlling the stresses by grading the electrostatic fields is, after all, a clear-cut principle. In contrast, the thought that the insulation can simply be graded in parts to combat uncontrolled impulse stresses is simply

an aspiration. It would appear to mean that one must (*a*) determine where the undue stresses appear and then (*b*) modify the insulation, knowing only too well that (*b*) nullifies the accuracy of (*a*).

What the shielding aims at is subduing the generation and movement of the peak impulse voltages through the windings, so that normal and possibly reduced insulation will be satisfactory. Apparently this can be done now without any real increase in the cost of the transformers.

The author's solid model is full of significance. The high ridge of pressure above the incident value can be followed through the winding to beyond the centre and during a definite lapse of time. The slopes to this ridge which are the measure of the stresses between turns and coils can be sensed, and so it is seen how the peak and slope stresses both sweep through nearly all parts of the winding.

Here is support for those who would multiply the insulation through all the winding, and so make an expensive and impractical transformer; but it is difficult ground for those who contend that the serious peaks and slopes are confined to small sections of the windings, and can be dealt with there without any use of the principle of electrostatic screens or shields.

End turns could of course be formed into caps and cylindrical shields and umbrellas for the main coils, to fulfil the same function as the author's, but these turns carry load and fault current and their need for mechanical support makes it clear that the appendix form of shield, which carries potential only, is preferable. At the same time the possibility of obtaining a useful degree of screening by some properly braced arrangement of end coils ought not to be lost sight of.

There is an aspect of electrostatic screening in relation to breakdown between turns and between coils which I want again to bring to the notice of those interested. It is generally admitted that inter-turn breakdown comes as a surprise to those who try to estimate the magnitude and duration of the stress involved. A winding is a complex mass of conductor and insulation in which defects can escape detection by tests, but there is more in it than that. The theory of progressive damage is often invoked, but the stress is so extremely evanescent and the idea that the hammer blow will always fall at exactly the same spot is so very remote that the reasoning lacks strength.

However, in the case of faults in service where inter-turn breakdown can be detected as the initial cause, it will almost invariably be found that it has occurred where there can be a strong electrostatic field across the major insulation. Several observations of this kind have suggested to me that the inter-turn or inter-coil section breakdown always takes place in an atmosphere of corona formed by the impulse stress across the major insulation. The latter is very strong against these impulse stresses, for the corona streamers must be long and persistent to break it down, whereas the "slope" stress is acting across short spaces on insulation much weakened by the corona radiants. Moreover, power arc, needing very little voltage to follow, also finds very little of a self-sealing character such as oil in its path.

It will be noted that any tendency for major corona will always determine where the hammer blow can fall with effect.

The following are some of the obvious remedies for this condition which I have suggested to transformer designers.

Screens inside the winding coils and where the major electric fields are strong, should be interposed to take the corona off the turns which otherwise would be exposed to this risk. Each screen should be connected to the coil section protected, and not to the terminal of the winding. If the transformer also has impulse stress grading shields of the author's type, any extra shunt capacitance introduced by the corona protective screens will have to be compensated by the external shields.

In the case of disc coils the inside turns are corona screens except for the effect at their edges. They should be given extra lappings of insulation to strengthen it against breakdown to the turn above, which may be exposed to the edge corona.

In a similar way the inner layer of wire-wound coil sections should have the wire insulation reinforced in liberal degree, thus increasing the conductor spacing. Inter-turn cords might also be wound in.

Reverting to the disc-coil sections, it must be understood that it is possible to have high impulse stresses between the discs of a deep type of winding which may be dangerous if the cross connection is outside. It may be enough to form inter-coil corona and in consequence to weaken the inter-turn insulation. There is also a tendency for these inter-coil stresses to set up incipient discharge over the surfaces of the spacers, which can have destructive effect on the edge insulations of adjacent turns. Breakdowns like this have been observed in impulse-tested transformers. Deep disc windings should have more inter-turn insulation than shallow ones.

I hope this reference to impulse corona effects will not be considered to be outside the scope of the paper. I want it to be recognized that electrostatic screening can be made to serve a double purpose, and I hope that research will be directed to that end.

[The author's reply to this discussion will be found on page 453.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 26TH FEBRUARY, 1940

Mr. C. G. Giles: This paper is interesting in showing how the impulse level of transformer windings may be increased in a relatively cheap and simple manner by the judicious use of capacitance shields applied to the outside of the high-voltage winding. But I feel sure that engineers would have found the paper more valuable if the author had backed up his experimental results by including some actual impulse-voltage breakdown figures of the shielded and unshielded windings. Have any impulse breakdown tests been carried out on completed transformers with both types of windings, and do the results confirm that the shielded winding has an impulse breakdown strength some 2 to 3 times that of the unshielded type? In the shielded type, where is breakdown most likely to occur? It would have been interesting to have seen the impulse-voltage distribution curves of the

two types of windings with the neutral end isolated; is the shielding equally effective under these conditions?

Referring to the calculating board, are the network units capacitances or resistances? Is an a.c. or a d.c. voltage applied to the network?

Perhaps the author would state what wave form was used in obtaining the test results shown in Figs. 10 and 11.

Mr. G. W. B. Mitchell: The transformer user, when considering the lightning protection of transformers, is faced with two problems: Firstly, how much money it will pay him to spend; and secondly, what is the best way of spending that money?

The answer to the first question can only be obtained from a study of statistics relating to the frequency of transformer breakdowns, and these statistics are still far from complete. The answer to the second depends on consideration of the technical problems involved, which is the subject dealt with in the paper. It also depends on the cost of applying the various alternative forms of protection.

The technical problem can conveniently be divided under the headings of " major insulation " and " inter-turn insulation," with which, for convenience, I couple " inter-coil insulation."

The author contends that normal major insulation is generally adequate, even in districts subject to severe lightning, and available statistics certainly seem to bear this out. In fact, if major insulation were the only factor to take into account, I doubt whether it would be worth while considering special protective measures at all.

The remaining problem is to deal with inter-turn and inter-coil stresses. Two general methods are available: firstly, the provision of external protective devices; and secondly, the co-ordination of insulation and capacitance grading in the transformer itself. These two methods may also be used in conjunction with each other.

External protective devices fall under the general headings of: (1) rod-gaps, (2) high-speed arc gaps, (3) lightning arresters, (4) surge absorbers, and (5) shunt capacitance.

Rod-gaps are the simplest devices, and have been widely used. My own feeling, however, is that they are almost useless for protecting a normal transformer, and may even make matters worse. In view of this I am particularly interested in Figs. 17 and 18 in the paper, relating to the effect of chopping a wave on the tail; as this is exactly what a rod-gap does, owing to its inherent time-lag in operation. Certain misconceptions regarding the use of rod-gaps have arisen, due to the fact that a large number of articles have been written on this subject, particularly in America, in such a way that without other information one might be led to believe that a rod-gap was the ideal way of protecting a transformer. The important qualification is that a rod-gap should be used in conjunction with a capacitance-graded transformer. The collection of statistics regarding the operation of rod-gaps is also likely to be misleading, as the fact that a rod-gap has been found to flash-over does not necessarily indicate anything except that the transformer has been subjected to a surge which it would probably have withstood in any case, without any external protective device. I should particularly like to have the author's opinion on this point.

High-speed arc gaps, which were referred to in a recent paper* read before The Institution, are designed to break down early on the front of the wave, and, as the author shows in Fig. 19, this effects an immediate reduction in the voltage stresses in the transformer without leading to any evil after-effects. The difficulty in employing high-speed arc gaps is that, unless some form of arc-suppression device is used on the system, the follow-through power current arc in the gap will cause the circuit to trip each time the gap operates.

A lightning arrester consists essentially of a high-speed gap in series with a special type of resistance material designed to suppress the follow-through power current. Lightning arresters are therefore particularly suited for installation on systems having solidly-earthed or resistance-earthed neutrals. They are more expensive than high-speed arc gaps.

The action of surge absorbers has been fully described in a recent Institution paper† and is not to be confused with the action of shunt capacitance, although both devices may be termed " smoothing " devices as compared with " chopping " devices belonging to the " gap " family.

It would seem from the foregoing that the best line of attack at present is to install high-speed arc gaps and ordinary transformers where arc-suppression devices are also used on the network. In this country this applies principally to lower-voltage systems, and I would add that there are, in any case, certain difficulties in providing high-speed arc gaps of the enclosed type for higher-voltage systems owing to their tendency to become unduly large. One of the advantages of high-speed arc gaps, however, is their comparative cheapness.

Where arc-suppression devices are not used on the system, it seems to me that the choice is lightning arresters or surge absorbers, used with ordinary transformers, and capacitance-graded transformers, either by themselves or with, perhaps, the addition of rod-gaps.

The addition of shunt capacitance is a very expensive method, except where the necessary capacitance has, in any case, to be provided in the form of a cable termination to an overhead line. Cable terminations do not act as simple capacitances, and the effect they have on surges is largely controlled by the internal reflections of the wave which take place at the cable ends.

We arrive here at the point where only a study of comparative costs can decide between the use of capacitance-graded transformers with rod-gaps or even without external protective devices at all, and ordinary transformers with efficient external protective devices. To be efficient, external protective devices must be installed as close as possible to the transformer, and preferably directly connected to the transformer terminals. This is not always easy to do, and the point is therefore one in favour of the capacitance-graded transformer with or without rod-gaps which are easily mounted. Small distribution transformers which are properly designed and which employ bobbin-coil windings can economically be left to look after themselves.

Before concluding, I would say that I have merely

* H. W. Clothier, B. H. Leeson and H. Leyburn: *Journal I.E.E.*, 1938, **82**, p. 445.

† J. L. Miller and J. M. Thomson: "The Surge Protection of Power Transformers," *Journal I.E.E.*, 1938, **84**, p. 187.

considered transformer protection. At large and important stations in lightning areas it may be desirable to use capacitance-graded transformers and in addition to install other devices on the incoming line terminations primarily to protect other station apparatus. I have deliberately omitted to refer to the co-ordination of line protective devices, which is also important.

I regret that it was not possible for the author to deal with the question of voltage/time characteristics, and hope that he will do so at a later date.

Mr. G. H. Hickling: A surge which penetrates the shielding winding must set up voltage oscillations within it owing to being reflected at the open end of the shield coils back into the main winding. Has the author investigated the effects which these oscillations produce on the stresses in the winding?

What are the limiting factors determining the design of the shields, and the extent of correction provided? It would appear that the limitation of the capacitance between the shielding and main coils due to the necessary insulation and the necessarily small dimensions of the shielding turns, and also the distance which it is permissible to carry each individual section of shielding down the winding (also governed by the insulation thickness), are the two important factors; do these in fact determine the curve of initial voltage distribution which the design aims at producing? What is the special virtue of the sine-wave curve of deviation from the linear initial distribution? Whilst this is clearly a satisfactory compromise, it is not so evident what advantages are gained from strict adherence to this curve. The envelope of maximum oscillations given in Fig. 7 is shown as being exactly tangential to the 100 % voltage line, in comparison with Fig. 10(*a*), for example, in which oscillations up to 115 % are indicated. The same remark applies to the diagrams accompanying the patent specification referred to in Item (7) of the Bibliography, and from a rapid perusal of the text the impression might be obtained that this condition was a necessary consequence of the "sine wave" shielding. In fact it may readily be shown that in a perfectly uniform winding, with earthed neutral, voltages will never occur at any point in excess of the amplitude of the applied impulse. Such excess voltages do occur in practice as a result of reflections in the winding at points of discontinuity, due to the provision of reinforced insulation on the end coils. It would therefore be interesting to know whether it is found possible to dispense with such reinforcement of the end-turn insulation in transformers equipped with shielding as described in the paper, or whether the reinforcement is appreciably less than in a normal winding.

Considerable stress is laid in the paper on the *initial* voltage distribution and on the effect of the higher space harmonics. It should, however, be pointed out that the subsequent oscillations resulting from the "fundamental" are less damped, and produce stresses of longer duration, than those resulting from the higher harmonics of the space curve. They are consequently most likely to cause breakdown in the regulating tapping section or at the neutral end of the winding, their importance being increased by the time-lag effect in insulation breakdown. It is therefore particularly to be noted that the improvement in inter-turn stress produced by the shielding, as shown by the oscillograms, progressively diminishes at increasing distances from the line terminal.

I am particularly interested in the measuring technique used by the author—especially in the recurrent-surge system and the device used for chopping the impulse at a variable time-interval from the commencement. With regard to the high-voltage oscillograph measurements, is the instrument used by the author of the type in which high voltage is applied directly to the deflecting plates, or was some form of voltage-divider used? The latter method appears to introduce difficulties in recording the differences between two nearly equal voltages of relatively large amplitude.

Mr. G. Pember: The paper deals exclusively with the stresses in the insulation of transformers of the core type, under surge conditions. In a shell-type transformer the mean length of turn is usually much greater than in the similar core type, and this leads to a correspondingly greater voltage per turn. It would seem probable, therefore, that the inter-turn insulation would be more severely stressed by an impulse voltage. Sometimes in the shell-type transformer the high-voltage winding is divided and sandwiched between sections of the similarly-divided low-voltage winding. This would modify very considerably the distribution of series capacitance between the high-voltage coils. Can the author give some idea of how electrostatic shields would be designed for this type of winding?

In a core-type transformer having the delta-connected high-voltage winding divided into two parts, connected in series and placed concentrically over the low-voltage winding, there will be different shunt capacitances for the two parts and non-uniformity in the series capacitance at the end where they are connected. Do these differences introduce any serious difficulties into the calculation of suitable shields?

Is it now standard practice for the author's firm to fit electrostatic shields with co-ordinated insulation to all their high-voltage transformers? If not, to what proportion of their output are such shields now being applied?

Mr. E. C. Rippon: In a recent review of progress* reference is made to two methods of designing transformer windings with regard to surge conditions: (1) "To proportion the inter-turn and inter-coil insulation adequately to resist, at all points, the surge voltages occurring." (2) "To provide the winding with some form of static shields. . . ." The statement continues "Both methods are employed, the former being the more predominant in this country." It is difficult to reconcile this statement with the author's opinion (page 441) that it would appear to be extremely difficult, if not impossible, to provide increased insulation sufficient to give the necessary inter-coil safety factors. The fact remains that this can be and is being done up to the highest voltages used in this country. The author refers to the testimony given by the unbroken service record of several million kVA of shielded transformers; but surely this is a very small percentage of the total kVA of transformers of conventional design operating in all parts of the world.

It is clear from Fig. 8 that the author has himself overcome the difficulty in providing adequate insulation

* *Journal I.E.E.*, 1940, **86**, p. 195.

to meet the maximum inter-coil stresses. Typical arrangements of shields are shown, and it will be of interest to compare the voltages appearing, say, between coils Nos. 28 and 27 for shielded and unshielded windings. For this purpose the distribution curves given in Fig. 11 may be used, since they relate to tests on an actual transformer. Coil No. 28 represents approximately 16 % of the total winding length, i.e. 84 % of the winding from the neutral end. Without shields, the voltage appearing across coils Nos. 28 and 27 is approximately 5 % of the applied impulse voltage. With a shielded winding, however, the voltage between these coils appears to be of the order of 55 % of the applied impulse voltage (due to the shielded winding connected to the terminal end), i.e. the insulation of the shields to the coil and the insulation between shields at this point must be as high as that provided in a normal transformer at the extreme ends to meet similar conditions.

It is at once obvious that the voltage stresses given in Table 2 should be supplemented by a column giving the stresses between the shielding winding and the main transformer winding. It will then be seen that the stresses in a shielding winding, at some points, are as high as, if not higher than, those in a transformer of conventional design.

The inter-coil stresses given in Table 2 for unshielded windings are extremely high and can only be accounted for by the small number of coil sections employed. It is apparent that the inter-coil stresses may be reduced by increasing the number of coils in the winding, and that in shielded windings the number of coils appear to be less than the number employed in conventional transformer designs. For instance, in Fig. 9 an 88-kV transformer is shown with about 40 coils. In a conventional design the total number of coils would be considerably increased, thus reducing the voltage between coil sections.

The term "mechanical considerations" (page 431) is no doubt intended to cover such faults or accidental injuries to the conductor insulation as may be the cause of breakdown. In other words, the insulation should be thick enough to stand some damage without this causing dangerous reduction of the electric strength; for example, if the outer layer of paper is torn, the remaining layers should suffice for safety. Obviously if there are only two layers of paper and one becomes torn, the electric strength is reduced by approximately 50 %; but if there are, say, 6 layers the strength is only reduced by approximately 16 %. This is a strong argument for a reasonably thick covering all through the winding, as there is no doubt that a large percentage of failures are primarily due to undetected mechanical damage, perhaps precipitated by surges.

In this respect the requirements laid down in B.S. No. 422—1931 for conductor insulation are grossly inadequate, and most purchaser's specifications are now asking for much higher insulation levels. The additional insulation which has to be provided on the conductors and between the coils to meet these increased test voltages greatly increases the mechanical strength and the stability of the whole winding; that is, both the insulation and the mechanical factors of safety are increased—a most important point in the design of large high-voltage transformers.

Mr. B. C. Robinson: The author's results show the effect of shielding the windings of transformers with the neutral (star) point earthed. On page 433 it is stated that the shielding is equally effective with delta-connected windings. A third condition, which is not dealt with, is that where the neutral point is isolated. When the impulse is applied to one phase only of a 3-phase transformer, the other phases being earthed, oscillations similar in general shape to those obtained with an earthed neutral point occur. If, however, the impulse is applied to all three phases simultaneously the voltage at any point describes damped oscillations about the applied impulse wave-form with an amplitude depending on the difference between the initial voltage at the point considered and the applied impulse. I should be glad to know how far these oscillations may be reduced in magnitude by the use of shields such as are described in the paper. Also, is the shielding for this case the same as for a transformer with the neutral earthed?

In his verbal summary of the paper the author stated that no shielding is used below 44 kV. In transformers where the low-voltage side operates at a greater voltage than this, is it necessary to shield both windings separately if both are connected to transmission lines, or does one set of shielding suffice for both?

In regard to Fig. 17, I think it would be a help in assessing the efficacy of the shielding if some indication —preferably in the form of an oscillogram—were given of the magnitude of the applied voltage.

Finally, I should be interested to have some details of the method used to obtain the chopped impulse on the recurrent-impulse generator.

Mr. V. Easton: With regard to the insulation stresses due to power-frequency voltages, it is suggested that a transformer may reasonably be operated at 75 % over-voltage, i.e. with one line earthed, for a maximum period of 10 hours every 3 months. In this country, where it is usual to earth the system neutral either solidly or through a low resistance and to provide instantaneous protection against faults to earth, the over-voltage due to a fault will persist for, at most, a few seconds. With a system earthed through arc-suppression coils, in the event of a permanent fault developing on one line, it is the usual Continental practice to leave the coil in circuit until the fault has been located and arrangements can conveniently be made to isolate the section. This may take several hours, and it would be possible for these conditions to be maintained for more than the specified period. If this is likely to cause damage to transformers the arrangement is to be preferred whereby the suppression coil is short-circuited if the fault persists for more than a few seconds.

Referring now to the stress due to surge voltages, the remark that lightning, as a source of over-voltage, is probably more important than switching, is an understatement and is inconsistent with the information given later in the paper. Since the voltage distribution between turns and coils for a switching surge is approximately the same as for a power-frequency surge, the maximum over-voltage between turns and to earth is of the order of 5 times normal. With lightning surges and transformers of normal design the voltage to earth may be 20 times, and the inter-turn voltage 50–75 times, the nominal value.

The application of electrostatic shields appears to be effective in reducing the ratio of the surge to the power-frequency inter-turn voltage to about one-third the usual value, and it would be interesting to know whether it has any effect on the voltage to earth; judging by the curves in Fig. 14 there is no appreciable reduction. All the tests appear to have been made with the neutral point of the windings earthed solidly, and while this condition usually holds good for transformers designed for the higher voltages there are many systems in which the neutrals are either isolated or else earthed through a resistor. It would be interesting to know whether any oscillograms were taken with the neutral point isolated.

I should like to support the author's opinion that the limitation of the amplitude of surges is best achieved by an arrester which incorporates a resistor of the ceramic type. In addition to the advantages he mentions, the transfer from the non-conducting to the conducting stage and vice versa is less severe and the stresses on the inter-turn insulation correspondingly reduced. The curves in Fig. 20 are very interesting and show that the distribution of the initial surge voltage is approximately uniform. The curve is similar in shape to that recently published in the *Journal** for high-voltage alternators of the concentric-conductor type, and it is reasonable to expect that this type of transformer without special protective gear would be as immune from failure due to surge voltages as the concentric-conductor alternator has proved in service under similar conditions.

At one time it was considered that the interposition of a transformer between the overhead distribution system and the lower-voltage apparatus gave effective protection to the latter. It is now agreed that this is incorrect; surge energy may be transmitted through a transformer in four different ways, one of which depends on the capacitance between the high- and low-voltage windings and earth. Electrostatic shields will have the effect of modifying the transformer capacitance, and it would be interesting to know whether any investigations have been made into the effect of this change on the magnitude of the surges transmitted to the l.v. windings. If the improvement in the surge-voltage distribution in the transformer is obtained at the expense of an increase in the stress on apparatus connected to the l.v. windings, a system with shielded transformers may actually prove less satisfactory and have more frequent breakdowns than one on which transformers of normal construction are installed.

Mr. M. Waters: The non-resonating transformer was designed to give an insulation-stress distribution along the winding under surge conditions identical with the power-frequency distribution. It was expected that by this means all internal oscillations would be eliminated and the stress produced by a given lightning surge would be made a minimum. In theory the non-resonating transformer certainly approaches the ideal, and one would have thought that, if it could have been made reasonably cheaply, it would have come to the fore rapidly and become very popular. Far from this occurring, however, we find that the makers of the non-resonating transformer have abandoned this design except at very high voltages, and now install electrostatic shielding which produces a stress distribution only slightly better than that of an unshielded transformer. Fig. 11 shows in effect how far they have departed from the ideal, and how close they are to the unshielded design. This retreat from the ideal begins to throw doubt upon the necessity of providing any shielding at all, and certainly seems to show either that the non-resonating transformer must have some very grave disadvantages not associated with the stress distribution or that it is so expensive to make that it is quite unable to compete with ordinary unshielded transformers at any but the very highest voltages. I think that the author should have given in greater detail the reasons, both in regard to design and in regard to relative costs, which led to the abandonment of the ideal design in favour of one which gives a distribution only slightly better than that of an unshielded transformer.

Mr. N. S. Tennant (*communicated*): I should like to ask the author's views on the application of his type of shield to small transformers such as are used on rural distribution lines at voltages of 11 kV and 22 kV. This class of transformer is usually pole-mounted, is exposed to lightning surges and is a not-infrequent source of trouble due to failure of the insulation on the primary side. These transformers are seldom duplicated, and a breakdown leads to a prolonged stoppage of supply. The necessity of restricting the iron losses so far as possible leads to a restricted winding space and hence less insulation than would be used were reliability the only consideration.

It appears to me that this is a field in which the device described by the author might find a wide application.

THE AUTHOR'S REPLY TO THE DISCUSSIONS

Mr. H. L. Thomas (*in reply*): Mr. Marshall has contributed an interesting tabulation comparing results of breakdown tests on samples of inter-turn insulation as actually used by five different manufacturers. It is understood that the column headings refer to the specified test voltage for the various grades of inter-turn insulation, i.e. full line voltage for the maximum degree of reinforcement, graded to one-third of line voltage, and finally, one-fifth of line voltage for the main body of the winding. The selection of the minimum amount of inter-turn insulation in each case has therefore already been made by the Specification, and the designer does not have a free choice, except in so far as he may use more insulation than the minimum required to meet the Specification.

It is interesting to learn that, in Mr. Marshall's experience, no case has occurred of failure of a transformer due to switching surges. It is also of particular interest to note that on the British 132-kV system, on which the neutral is earthed at every transformer, a 26-in. rod-gap has been found to be subject to only occasional switching flashovers.

Regarding the impulse voltage which a transformer can safely withstand, it is possible to design transformers to withstand an impulse acceptance test using

* *Journal I.E.E.*, 1940, **86**, p. 366.

a voltage of standard wave-form and of any specified amplitude. It is the responsibility of the user, and not of the manufacturer, to decide what this demonstrated amplitude or level shall be, and also to ensure that suitable measures are adopted to limit any surges in operation to a value not exceeding this level.

As Mr. Norris observes, the principles underlying surge-voltage distribution in transformer windings were actually appreciated by some investigators a very long time ago, and to some extent, also, the basic ideas of electrostatic shielding have been known almost as long. The shields referred to in the Haefely patent cited by Mr. Norris appear, however, to be more in the nature of power-frequency corona shields than for the purpose of control of impulse-voltage distribution.

The "non-resonating" winding utilized in the 500-kV transformer built in 1923, mentioned by Mr. Norris as illustrating inherently uniform surge-voltage distribution, I presume to have been of the multi-layer concentric type. High-voltage testing transformers, and other high-voltage transformers of small kVA capacity, lend themselves well to this form of high-voltage winding; and indeed, many such transformers have been built by the firm with which I am associated.

Mr. Norris suggests that it has been found possible so to proportion a transformer winding that the insulation is everywhere co-ordinated with the surge-voltage stresses. This is a principle of considerable interest, and the result is of course precisely what is achieved by the shielded winding, but with the advantage in the case of the latter that the "best" proportions of the transformer winding need not be interfered with, and may be freely chosen so as to result in the optimum design as dictated by the more usual factors. In this connection the remarks of Mr. Whitcher, in the first paragraphs of his contribution to the discussion, are of interest, and I would refer also to my reply to Dr. Billig.

It is gratifying to have support from Mr. Norris in the conclusion that inter-coil insulation is the principal problem in connection with impulse stresses and that inter-turn insulation is, in general, of secondary importance. From the very early conceptions of concentrations of stress across the end turns of a transformer winding, there has arisen the deep-rooted impression that large amounts of inter-turn insulation and of end-turn reinforcement constitute the criterion of a good transformer, from the impulse-strength standpoint. In the light of present-day knowledge, however, it is clear that such an impression is mistaken.

Dr. Allibone refers to the cost of the simplified shielding, which he rightly presumes to be "fairly cheap." The cost of the material involved is almost negligible compared with the cost of winding, and as the shields are applied as part of the winding itself, the amount of labour involved is not great. As far as what Dr. Allibone terms the "investigational work" is concerned, the shields for any particular transformer are quickly designed with the aid of the calculating board.

With regard to the linear or "non-resonating" shielding, I agree with Dr. Allibone in his implication that relatively large values of capacitance are required at the extreme line end of the winding in order to satisfy the theoretically ideal requirements for producing uniform voltage distribution. In actual practical applications, however, the departure from perfectly linear distribution is not as great as might at first sight be expected. In general, it is only over the first few coils at the line end of the winding that the shield capacitance may fall short of the theoretical requirement. Inspection of formula (1) in Appendix 1 will show that the shield capacitance decreases rapidly as x, the percentage turns from earth, decreases. Again, the radial shield will help towards compensating any deficiency in the axial shielding at the extreme line ends. In any case, a departure from linearity of the voltage distribution at the extreme line end will do no more than produce a slight increase in the stresses over the first few coils, which is of no consequence in practice, since no attempt is made to eliminate entirely the end-turn and coil reinforcement.

Dr. Allibone refers to the axial stress along the major insulation and gives figures purporting to show the degree of effectiveness of the shielded-winding transformer in reducing this. In quoting these figures, he has apparently made no allowance for two important factors: (1) that insulation breakdown, when the dielectric field is not uniform, is determined by the maximum and not the average stress; (2) that oscillation voltages as well as initial voltages must be considered when comparing maximum axial voltage-gradients.

Taking the figures which he quotes from the initial distribution curves of Fig. 11, the *average* gradient across the first 20 % of the winding at the line end is reduced from (80/20 = 4) to (65/20 = 3·3), i.e. a reduction ratio of 0·82 to 1. The *maximum* axial gradients are, however, the figures which should be compared, and must be measured over a small increment of the winding at the line end. For the purpose of such a comparison, the top figures in Cols. 1 and 5 of Table 2 may be used, from which it will be seen that the maximum gradient is reduced from 77 to 25·6, i.e. a reduction ratio of 0·33 to 1.

Dr. Allibone asks whether reinforcement of end-turn insulation is eliminated when the simplified shield is employed. The answer to this is really indicated at the beginning of his own preceding paragraph. Since the simplified shielding aims not at removing but rather at reducing the stress concentrations, some degree of end reinforcement is still required.

Regarding the use of external capacitors, the firm with which I am associated was, it is believed, the first actually to employ such. Shields as described in the paper are, however, considered to be more suitable as a practical and commercial proposition.

As Dr. Allibone rightly observes, tests to destruction on full-size high-voltage power transformers are very expensive. Nevertheless, shielded windings of the type described in the paper have been impulse-tested to destruction, and their impulse breakdown strength has been found to be considerably higher than that of the corresponding unshielded windings, in accordance with design expectations.

Referring to the transference of surges to the l.v. circuit, there does not seem to be much danger that this will cause high internal voltage-gradients in the l.v. winding. The possibility of a high terminal voltage to earth resulting from this cause, and also from any external cause in the l.v. system, should be countered

by the provision of suitable amplitude-limitation external to the l.v. winding itself.

The support given by Dr. Miller to many of the conclusions contained in the paper is greatly appreciated. My reference to the effect of reinforced turn insulation could well have been amplified, but I would point out that this particular section of the paper was intended only as a brief résumé of the general effects of impulse voltages on transformer windings. With heavy end-turn reinforcement, it is certainly possible to encounter maximum stresses at points other than the line end.

I agree with Dr. Miller's comment that chopping on the front of the wave can produce high inter-turn gradients at the line end of the windings. These voltages arise from oscillations of far higher frequency than those involved in inter-coil voltages such as are shown in Figs. 18 and 19; occurring, in fact, within the wave-front time. With reference to the suggestion that rod-gap flashover on the front of a steeply rising wave will involve greatly increased voltage amplitude, it seems to me that if a rod-gap is to be used as the sole means of surge-voltage amplitude limitation, then this possibility should be taken care of by setting the gap spacing at a suitably low value.

Dr. Miller asks about the use of the calculating board in determining impulse-voltage gradients at points some distance from the line end of the winding, and refers to the occurrence of these stresses sufficiently late in time to necessitate the inclusion of inductive elements in the network. In answer to this, I would say that the calculating board described in the paper is used only to determine the initial distribution, i.e. as determined purely by electrostatic capacitance. It is possible to estimate the maximum oscillation-voltage amplitude between any two points in the winding, partly by analysis and calculation based on the initial distribution, and partly from data accumulated from actual tests on many different transformers. The agreement between the calculating-board estimate and actual test measurement of initial impulse-voltage distribution in a typical case is shown in Fig. 24 of the paper.

Dr. Billig's remarks relating to breakdown of insulation through thermal instability are interesting. The figures which he quotes from Sections (2) (*a*) and (2) (*b*) are, however, only intended to be of a very approximate nature, and are intentionally conservative.

Dr. Billig agrees that the maximum deviations from uniform voltage distribution in the conventional design of transformer occur between coils. He claims, however, that these are easily taken care of by reinforced insulation. A generalized statement such as this needs substantiation, or at least some qualification. How is this reinforced insulation to be applied? If in the form of increased conductor insulation, then it will most certainly affect adversely the impulse-voltage distribution. If in the form of coil taping or collars between coils, then it will result in increased cost and dimensions of the transformer, though possibly in this case the impulse-voltage distribution would not be as greatly affected. In any case, it is questionable whether the degree of perfection attained by the shielded-winding transformer could be approached by merely using increased insulation, without seriously affecting the otherwise normal proportions of the transformer. I disagree with Dr. Billig's suggestion that shields such as those shown in Fig. 8 interfere in any way with the cooling of the winding. The oil ducts are unimpeded by the shields, and the circumferential surface of the outer turn covered by the shield is actually only a small proportion of the total cooling surface of the coil. I would question the statement that the vertical circumferential surface of a coil is the most valuable in regard to heat dissipation.

Dr. Billig's remark regarding the number of turns traversed by a surge before the peak arrives at the transformer terminals may be expressed in another manner, by saying that the "initial" distribution is rendered less steep than the theoretical when the wave-front time is long compared with the shortest periods of internal oscillation in the winding. This point is certainly borne in mind, but, as explained in the paper, the design of shielded windings is based on the worst possible initial distribution, so that the transformer is then capable of withstanding the effects of any wave front, however short, which may be encountered in service.

Mr. Lacey refers to a possible difficulty in estimating the series capacitance of a transformer winding. Actually, we find no more difficulty in this than in the case of the shunt capacitance. All of the calculations are of necessity approximate, but are based largely upon fundamentals and modified to some extent empirically. Mr. Lacey's remarks regarding bobbin-coil windings are reasonable, and I agree that perhaps one should not expect the same degree of uniformity of voltage distribution within a single coil when that coil is inserted in a stack consisting of a number of such coils. Tests, however, show that the distribution is still remarkably good.

There is sound reason in Prof. Fortescue's objection to some of the terminology associated with "shielded" transformers. It is to be feared, however, that such terms have now become so widely known and used that it would be difficult to eradicate them. Personally I consider that the term "non-oscillating" is preferable to "non-resonating."

Mr. Hansell appears to require still more information than that contained in the paper in order to convince himself that a shielded winding is "better economically than one designed in the usual manner, with the insulation between the end turns increased so that it will withstand the transient voltage." The question of economics involves not only the first cost of the transformer and of repairs (if any), but also the cost, to the community, of supply interruptions. As Mr. Marshall mentioned in his remarks, lightning remains the one serious enemy to continuity of supply, and although failures amount to less than 1 % per annum it is very desirable to eliminate even that 1 %.

The comparative stress figures given in Tables 2 and 3 refer to transformers which, without their shields, are representative of ordinary normal design, having reinforced end-turn insulation. The application of shields effects a reduction in the inter-coil stresses to the extent of $\frac{1}{2}$ or $\frac{1}{3}$, and this is sufficient to ensure that the ultimate strength of the inter-coil insulation is at least as great as that of the major insulation, which latter then cor-

rectly establishes the insulation level of the transformer. Assuming that, in round figures, the factor of safety in the major insulation is 2 to 1, then under impulse test conditions the inter-coil insulation in the case of the unshielded winding would break down at between 67 % and 100 % of the test voltage applied to the line terminals. Thus, as one contributor to the discussion has expressed it, the normal transformer displays a "factor of weakness of about 1·5 to 1 in the axial direction." The elimination of this weakness in the positive yet simple application of the shields is their economical justification.

With regard to Mr. Hansell's questions in connection with Table 2, the figures therein relate to a high-voltage transformer of small capacity and having its end turns heavily reinforced in accordance with the customer's specific requirements. On the other hand, it is understood that the figures given in Mr. Hansell's Table B relate to a simple uniform winding. The maximum gradients shown in Table B appear to apply to the voltage across 1/12th (or 8·3 %) of the winding, which, I submit, is too large an increment to show up the real maximum gradient at the line end. In contrast with this, the maximum gradients shown in Table 2 for Sections 1–2 apply to the voltage across only 0·43 % of the winding, and thus represent the true maximum. The actual turn ratio which Mr. Hansell asks for was approximately 1 to 20. The distance from copper to copper between the two end sections was about 1·8 times the corresponding distance between sections in the body of the winding.

Mr. Hansell refers to the application of impulse voltages simultaneously to both ends of a delta-connected winding fitted with simplified shielding. In reply, I would state that we certainly have carried out such tests, though the condition envisaged is thought to be an unlikely occurrence in practice. As was expected, the reduction in the maximum amplitude of the mid-point voltage was found to be in line with the reduction in the amplitude of the fundamental space harmonic.

Table B is interesting, giving results of tests showing the reduction of inter-coil stress obtainable when capacitors are connected across portions of the winding. In principle, however, this method is no different from shielding, the practical difference being that, in the shielded winding, the capacitance elements are applied in a more convenient form direct to the winding, and are indeed virtually a part of the winding itself. Moreover, with the shielded winding the added capacitance is distributed around the winding, whereas with the external capacitors it is in the form of "lumped" constants.

Finally, Mr. Hansell expresses interest in the deduction of the safe period of operation of normal transformers under the fault condition of one line earthed. This is intended as an approximate "operating guide" for normally-insulated transformers when used on systems employing arc-suppression-coil earthing. It was deduced from actual experience supplemented by analysis of many tests on the voltage/time characteristics of typical transformer-insulation assemblies. This analysis can conveniently be summarized for practical application in the form of curves such as those shown in Fig. A. These curves really illustrate graphically the statements contained in Section (2) (*a*) of the paper.

I should like to thank Mr. Whitcher for his most interesting and useful contribution to the discussion. He gives support to the principles and application of electrostatic shielding in no uncertain terms, and also throws light on the possible effects of impulse corona across major insulation in causing impulse breakdown of inter-coil and inter-turn insulation. There is still much to be learnt about the real nature of impulse breakdown of insulation, and Mr. Whitcher's remarks contain valuable suggestions for future research. Mr. Whitcher's views on the "aspiration" to arrange and proportion the insulation of conventional transformer windings so as to make them self-protecting may be contrasted with the suggestions put forward by several

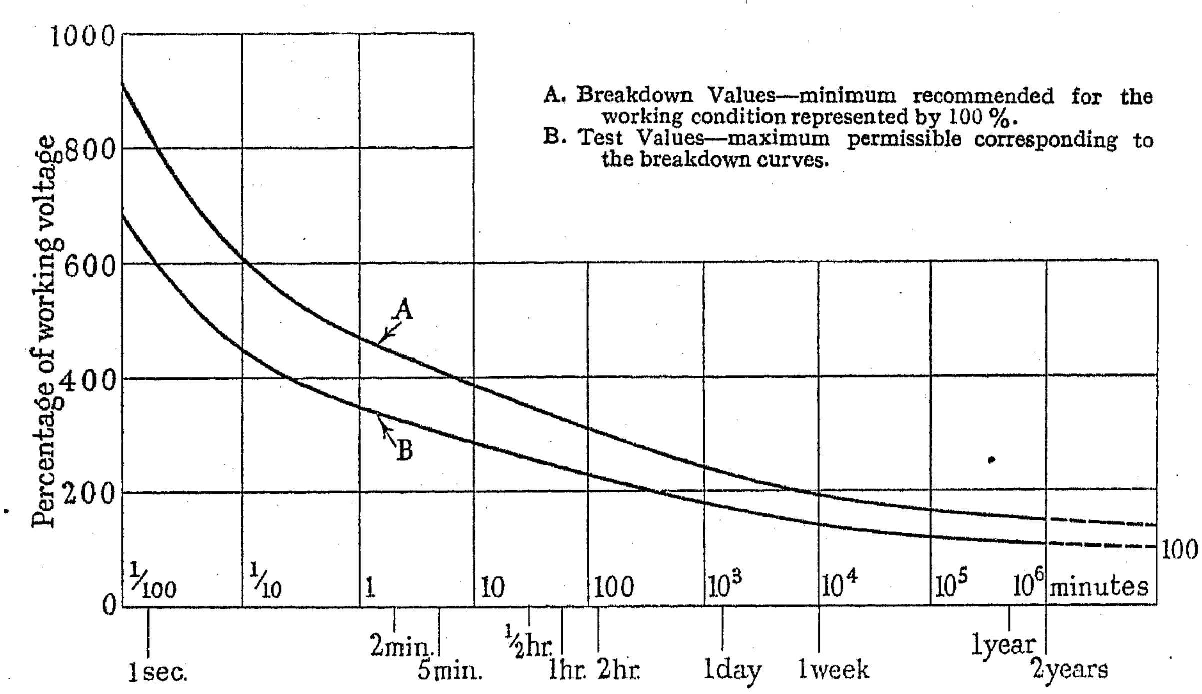


Fig. A.—Typical transformer insulation voltage/time curves; applicable to power-frequency stresses only.

of the other contributors to the discussion, both in London and at Newcastle.

Mr. Giles desires information regarding impulse tests to destruction on actual high-voltage transformers, with and without shields. For this, I would refer him to my reply to Dr. Allibone's remarks in the London discussion. As to where the breakdown is most likely to occur, it is clearly stated in the paper that the basis of the design is to ensure that the major insulation establishes the insulation level of the transformer, and that other parts shall be made at least as strong. Hence in a shielded transformer, major insulation breakdown is to be expected before inter-coil or inter-turn breakdown.

Referring to the case of the isolated-neutral winding, the initial impulse-voltage distribution curve is in general very little different from that corresponding to the same winding but with earthed neutral. This is shown by the curves in Figs. 2A and 2B of a recent Institution paper.* Oscillograph tests taken on shielded windings show that the inter-coil voltages are not greatly affected by whether the neutral is isolated or earthed, and that the shields are just as effective in either case.

Mr. Giles asks about the network elements employed with the calculating board described in the paper. These are variable resistors, reciprocally scaled so as to be proportional to the capacitances which they represent. The voltage applied to the network is low-voltage direct current from a battery source. The wave form used in obtaining the impulse-voltage distribution curves shown in Fig. 10 was approximately 0·4/100 microsec., i.e. relatively short front and long tail as compared with proposed standard test wave-forms, so as to simulate the severest possible conditions. In the case of Fig. 11, the corresponding wave-form is given in Fig. 12.

Mr. Mitchell contributes a concise survey of available methods of providing surge protection for the transformers. This should constitute a valuable supplement to the paper, the scope of which did not warrant more than a brief mention of protective measures. I presume that Mr. Mitchell's implication, regarding the conclusions which may be drawn from the flashover of a protective rod-gap, is based on the characteristic of this rod-gap being such that flashover on the tail of a surge is much more likely than on the front. Also, comparatively low-amplitude surges are likely to occur much more frequently than those of sufficient amplitude or steepness to cause flashover on the front. A point which Mr. Mitchell does not mention (probably considering it well known) is that not only does a rod-gap possess an inherent time-lag in operation, but that, owing to the difference in the shape of the voltage/time characteristics of rod-gaps and of transformer insulation, a rod-gap which flashes-over on a very steeply rising voltage wave-front will not protect the transformer insulation unless the gap spacing is very low. Spacings on rod-gaps to meet such conditions are, in fact, so low as to introduce a fair risk of service interruptions due to normal switching surges. Hence, in general, it is likely that plain rod-gaps will not be set at a low enough spacing to ensure adequate protection against overstressing of end-turn insulation, particularly in the case of transformers having no means of controlling the internal stresses.

* *Journal I.E.E.*, 1937, **80**, p. 117.

In connection with the use of high-speed arc gaps, designed to break down on the front of an impulse-voltage wave, Mr. Mitchell refers to Fig. 19 of the paper as showing that no serious voltages can thereby arise in the transformer winding. This is correct if the device used has a truly "sphere-gap" characteristic, but, even then, high voltages may occur between turns.

With the use of any form of voltage-limiting gap, power follow-up current is liable to occur, but the suppression of such current is a separate problem from that of voltage limitation. The selection of the most suitable of the various available methods, including arc-suppression coil earthing, depends upon the system, and the service demanded.

Mr. Hickling makes reference to the possible effect of wave reflection from the open ends of the shields. The paper is concerned mainly with the practical results obtainable by adding electrostatic shields to a transformer winding, and any effect such as that mentioned by Mr. Hickling is but a component part of the voltages which are actually measured. Mr. Hickling's question regarding the extent of correction provided is presumed to mean the actual amount and type of shielding required for any given transformer. The degree of shielding is related to the voltage level of the transformer, and in practice this results in the smallest degree of shielding for the lowest-voltage classes, becoming progressively greater until at the very highest voltages either the sinusoidal or the linear shielding becomes desirable. The factors involved in what we may call the mechanical design of the shields are substantially as Mr. Hickling indicates, but we have not yet found them limiting in any case considered.

The advantage of the sinusoidal shielding is that the winding only oscillates as a whole, with the fundamental frequency, and hence there can be no local concentrations of stress such as are usually brought about by the higher harmonics. Whereas, with linear shielding, the voltage gradient (as compared with uniform distribution) anywhere in the winding is unity, with sinusoidal shielding it may be between the limits of 1 and 2, depending on the degree of shielding provided. Reinforced end-turn and end-coil insulation is used in conjunction with all types of shielding referred to in the paper, the amount of such reinforcement being properly co-ordinated with the shielding. The suggestion that a uniform winding not fitted with shields is free from high oscillation voltages to earth is incorrect, and is contrary to both theory and practice.

It is true that the oscillations corresponding to the higher space harmonics are more highly damped than the fundamental and lower harmonics, but I do not agree that there is a marked falling-off in the effectiveness of the shielding at progressively increased distances from the line end of the winding. Tests on a transformer having tappings at the centre of the winding, have shown that the voltage across the tap sections is reduced by the shields to the same extent as the reduction in the voltage across the line-end sections.

Referring to the high-voltage cathode-ray oscillograph tests mentioned in the paper, a capacitor voltage-divider was used; special precautions being taken to eliminate any errors due to difficulties such as those Mr. Hickling foresees.

In reply to Mr. Pember, shell-type transformers usually employ windings of much greater radial depth than are adopted in the corresponding core-type design, and this generally results in considerable concentration of impulse stress across the inter-turn insulation. The application of internal shields to shell-type transformers with interleaved windings is a matter to which I have given but little consideration, since my firm does not generally make such transformers. I was, however, recently concerned with the application of external capacitors to a bank of transformers having sandwich or interleaved windings with a number of high-voltage coils connected in series. In this case, the impulse-voltage distribution throughout the series-connected coils was greatly improved.

An arrangement of concentric windings such as that mentioned by Mr. Pember in his second paragraph certainly complicates the calculations, but the difficulty is overcome by employing a suitable network on the calculating board. Shielded windings are now used on practically all of the high-voltage transformers of large and medium capacity manufactured by the firm with which I am associated.

Mr. Rippon evidently belongs to the school of thought which claims that transformer inter-turn and inter-coil insulation thickness can be suitably selected, so as to achieve the desirable ideals set out in the paper. I would refer him to my reply to Dr. Billig and others in the London discussion, and to the remarks contained in the first paragraphs of Mr. Whitcher's contribution to that discussion.

In attempting to make deductions from Figs. 8 and 11, Mr. Rippon has apparently assumed that the particular grouping of shields and inter-coil connections shown as merely typical in Fig. 8, was used in the case of the transformer to which Fig. 11 relates, whereas actually this was not so. If, however, this is overlooked and one considers Mr. Rippon's deductions from Fig. 11, his figure of 5 % voltage across a pair of coils located at 84 % from earth in the unshielded winding is clearly only the initial value. The maximum voltage produced by the subsequent oscillations in the unshielded design will be very much greater than this, as shown by the lower oscillograms in Fig. 12, and in the third column of Table 2. The shields decrease, not increase, the surge voltages between adjacent sections, and I can assure Mr. Rippon that the voltage between the shield and the adjacent winding, and also between adjacent shields, with the type of shield under consideration, never reaches anything like the high value of 55 % erroneously deduced by him. The shield conductor is of course adequately insulated for the stresses which actually exist.

Mr. Rippon is incorrect in his inference that the shielded windings have a smaller number of coils than is adopted in what he terms "conventional transformer designs." Apart from the shields, there is nothing unconventional about the shielded-winding transformer. The winding proportions are determined by such ordinary design factors as reactance, losses, heating, etc., and the number of coils in the high-voltage winding is determined partly from considerations of power-frequency voltage between coils and partly from thermal requirements, in just the same way as for a non-shielded transformer. In any case, it is not correct to assume that increasing the number of coil sections will necessarily reduce the impulse-voltage stress between all coils; for although the figure of percentage turns between coils is thereby reduced, the gradient at some points (percentage voltage/percentage turns) is undoubtedly increased.

Dealing with the remarks of Mr. Robinson, I have already made reference to the case of the isolated neutral in my reply to Mr. Giles. In the theoretically possible case of equal impulse voltages simultaneously applied at both ends of a winding, the maximum oscillation amplitude to earth will occur at the centre of the winding. The reduction in this due to shielding would be in line with the reduction in the fundamental space harmonic. In the case of delta-connected windings, the shields are provided at both ends, so as to meet the possibility of surges entering at either end of the winding.

For a transformer having a l.v. winding of relatively high voltage, such as 66 kV, it might be advantageous to apply shields to this as well as to the high-voltage winding; but no such case has yet come under my consideration.

Regarding the applied wave corresponding to the oscillogram of Fig. 17, this was omitted owing to considerations of space. The applied wave in each case was substantially the same as that shown in Fig. 16, except, of course, that it was chopped on the tail. Up to the time of chopping, the inter-coil voltages shown in Fig. 17 are much the same as the corresponding ones in Fig. 16, so that I do not think that the omission of applied-voltage oscillograms in the case of Fig. 17 has in any way reduced the value of these illustrations in demonstrating the efficacy of the shielding.

The chopped-wave device on the recurrent-surge oscillograph is operated by the short-circuiting of the applied impulse voltage through a thyratron. The time at which the chop occurs is controlled by the voltage of the grid of the chopping thyratron, the time-delay in this voltage being determined by the discharge of a condenser through a variable resistor.

Referring to Mr. Easton's remarks concerning the operation of transformers under the condition of an earth fault on one line, it is certainly preferable that such conditions should not be allowed to persist any longer than is absolutely necessary, unless the transformers were specifically designed for such operation. The suggestion contained in Section (2) (*a*) should be recognized as being merely an approximate guide for operating engineers, particularly where arc-suppression coils are installed.

Mr. Easton asks about the effect of shields in reducing the voltage to earth. Actually, the maximum oscillation voltage to earth, even in an unshielded winding, is seldom greater than 110 % to 120 % of the applied impulse voltage. In general, the shields will prevent the voltage to earth at any point in the winding from ever rising above the amplitude of the applied impulse, as illustrated in Fig. 10. Mr. Easton quotes Fig. 14 as showing no appreciable reduction, but if he will measure the maximum amplitude of the oscillations shown against the figure 98·9, he will find that in the case of the unshielded winding the maximum is slightly greater than the amplitude of the applied impulse; whilst in the

case of the shielded winding, it is appreciably less than the applied voltage. As regards the effect of isolating the neutral, I would refer Mr. Easton to my reply to Mr. Giles.

Referring to the transference of surges from the high-voltage to the low-voltage circuit through a transformer, the application of electrostatic shields to the h.v. windings cannot produce any increase of the stresses on the l.v. side. The reduction of the oscillations in the h.v. winding as the result of shielding, will effect some reduction in that component of the transferred voltage which involves these oscillations, so that actually some benefit accrues.

The application of simplified shielding to all but the very highest-voltage classes of shielded-winding transformer is not, as Mr. Waters suggests, a retreat, but indeed represents progress in the scientific application of engineering research and knowledge to practical commercial manufacturing work. The basic principle of transformer insulation co-ordination is stated in the paper and consists in so designing the shielded windings that the impulse strength of the transformer is determined by the major insulation and not by the inter-coil or inter-turn insulation. The economic application of shielding requires no more than that this condition should be fulfilled, and as the result of development it has been found that the degree of improvement obtainable by "non-resonating" shielding is more than is necessary, except for the very highest voltages. In comparing the curves of Fig. 11 and stating that the shielding-winding impulse-voltage distribution is only slightly better than the impulse-voltage distribution of an unshielded transformer, Mr. Waters appears to have failed to appreciate the principles set out in this paper and also in other recent papers.* Mere visual comparison of initial voltage-distribution curves may not convey much to the uninitiated, but the oscillograms and tabulated results contained in the paper clearly substantiate the claims made for the shielded winding and indicate the benefits obtained not only initially but throughout all the subsequent oscillations.

In reply to Mr. Tennant, I do not consider that shielding as described in the paper is necessary on small rural distribution transformers operating on 11-kV and 22-kV circuits. Such transformers can be constructed with windings with an inherently good impulse-voltage distribution, and the minimum thickness of inter-turn insulation is dictated more by considerations of mechanical strength than of electric strength. The surge protection problem in such cases is then mainly a question of amplitude limitation.

In conclusion, I should like to express my satisfaction that so many engineers have taken part in the discussions and have raised points which emphasize the importance of the subject.

* *Journal I.E.E.*, 1937, **80**, p. 117; and 1939, **84**, p. 187.

INSTITUTION NOTES

ARRANGEMENTS FOR THE FIRST HALF OF THE SESSION

A circular describing the Council's policy in regard to the activities of The Institution during the first half of the 1940–41 Session has been sent to all the members.

From this circular it will be seen that the only Ordinary Meetings of The Institution to be held during the first half of the Session are the following:—

Ordinary Meeting, 24th October, 1940, *at* 2.30 *p.m.*, in the I.E.E. Lecture Theatre, Savoy Place, W.C.2, when the President, Mr. J. R. Beard, M.Sc., will deliver his Inaugural Address. A list of candidates for election and transfer approved by the Council for ballot will also be agreed for suspension in the Hall. (Note.—No advance copies will be available of the President's Inaugural Address, but it will be published in full in January in Part 1 of the sub-divided *Journal*.)

Ordinary Meeting, 14th November, 1940, at 12.30 *p.m.*, in the I.E.E. Lecture Theatre, Savoy Place, W.C.2, for the purpose of carrying out a ballot in respect of the candidates whose names were suspended at the meeting on the 24th October, 1940. (Only Corporate Members and Associates are eligible under the Bye-laws to participate in the ballot.)

A list of papers that would in normal circumstances have been read in London is given below, and copies of them can be obtained by members on application to the Secretary, with a view to the submission of written comments for publication in the *Journal* as a discussion with the author's reply.

It will be necessary for a separate application to be made for each paper that a member may require, and it is hoped that, in order to economize the Institution's limited supply of paper, members will only apply for those papers to the discussion of which they would wish to contribute.

The approximate dates on which copies of the papers will be available are indicated in the list.

Overseas members will, as usual, be able to obtain copies of the various papers from their respective Local Honorary Secretaries.

All the papers will be published in abstract in early issues of Part I of the sub-divided *Journal*, and subsequently in full (together with the discussion) in Part II or III.

List of Papers which were to have been read during the first half of Session 1940-41 and of which a limited number of advance copies will be available about the dates indicated.

Author	*Title*	*Copies available*
H. W. Grimmitt	"Electricity in Agriculture" (An introduction to a written discussion on the subject, for publication in the *Journal*, by H. W. Grimmitt, Chairman of the E.R.A. Committee responsible for the recent Report W/T2 on "A Critical Study of the Application of Electricity to Agriculture and Horticulture" by C. A. Cameron Brown, B.Sc.)	21 Nov., 1940
C. A. Mason and J. Moir	"Acoustics of Cinema Auditoria"	4 Dec., 1940
A. J. King, B.Sc. Tech., R. W. Guelke, Ph.D., C. R. Maguire, B.Sc., and R. A. Scott, Ph.D.	"An Objective Noise Meter reading in Phons for Sustained Noises, with special reference to Engineering Plants"	6 Dec., 1940
T. C. Gilbert	"Voltage-operated Earth-leakage Protection"	11 Dec., 1940
C. F. Booth	"The Applications and Use of Quartz Crystals in Telecommunications"	19 Dec., 1940
Dr. J. C. Chaston	"Materials for Electrical Contacts"	3 Jan., 1941
N. M. Rust, O. E. Keall, J. F. Ramsay, M.A., and K. R. Sturley, Ph.D.	"Broadcast Receivers: A Review"	8 Jan., 1941
W. J. Mason and S. A. G. Emms	"Paper Making"	23 Jan., 1941

STUDENTS' QUARTERLY JOURNAL

The *Students' Quarterly Journal*, which is published in September, December, March and June, is issued free of charge to Students and Graduates under 28. Other members, of any class, may obtain it on payment of an annual subscription of 6 shillings, which should be sent to the Secretary. The charge to non-members is 10 shillings per annum.

THE RECEPTION OF MEMBERS' CHILDREN OVERSEAS

Members will be interested in the following extracts from correspondence received from sister Institutions in the Dominions, which exemplify the spirit of co-operation uniting engineers throughout the Empire in the emergency with which the British Commonwealth is confronted.

The first letter is in reply to a communication signed by the Presidents of the Institutions of Civil, Mechanical and Electrical Engineers, thanking the Engineering Institute of Canada for the hospitality offered to children of members of the three home Institutions, details of which have already appeared in "Institution Notes."

The second, which conveys an offer of a similar nature from The Institution of Engineers, Australia, has been answered in terms expressing the Council's gratitude on behalf of all members of The Institution.

Members may obtain details of these offers on application to the Secretary.

The Engineering Institute of Canada.
26th August, 1940.

Sir Clement D. M. Hindley,
President, The Institution of Civil Engineers.

Mr. Asa Binns,
President, The Institution of Mechanical Engineers.

Mr. Johnstone Wright,
President, The Institution of Electrical Engineers.

Gentlemen,

Thank you very much for your kind letter of July 9th. I shall be very glad indeed to convey the thanks of your Institutions to the several Canadian engineering societies that have joined together to offer hospitality to the children of engineers in the United Kingdom.

It is doubtful if Canadian engineers have ever responded more enthusiastically to any project of national or international importance, and I am sure it will be of interest to you to know that great encouragement has come to the officers of our organizations from the memberships in all parts of Canada.

A copy of your letter has been sent to the President of each co-operating organization, and if I may take it upon myself in this instance to speak for all of them, I would like to assure you that any children you may send to us will be very welcome and will be cared for to the best of our abilities. We consider it a privilege to co-operate with our fellow engineers in this manner in the defence of Great Britain.

Yours sincerely,
T. H. HOGG
President.

The Institution of Engineers, Australia.
Science House,
Sydney, N.S.W.
27th July, 1940.

The Secretary,
The Institution of Electrical Engineers.

Dear Sir,

Evacuation of Children from Great Britain.

The Council of The Institution, at a recent meeting, gave consideration to a question which has been prominent in the minds of all Australians, particularly during recent months, when the safety of Great Britain has been threatened. I refer to the evacuation of children from your country.

We are, at the moment, conducting a survey of members of The Institution to determine the number of children for whom provision might be made, should means of transport to Australia be arranged in due course.

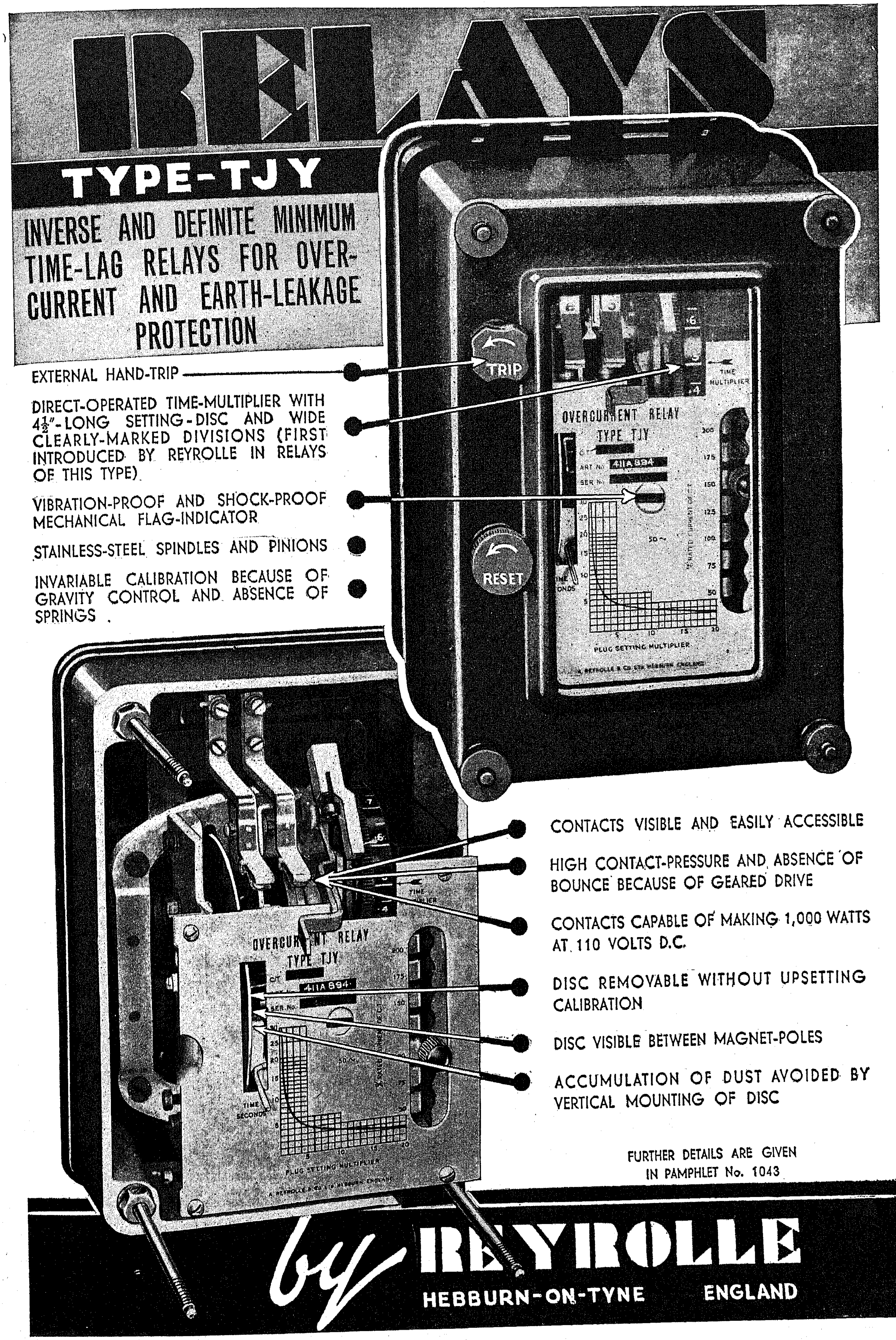
It is because we realize that many have already entered into private arrangements with relations and friends that the survey becomes necessary. Pending its completion, I am instructed to raise the inquiry with you as to whether you think members of your Institution would wish to accept any offer made on behalf of members of this Institution in Australia to take care of their children during the progress of hostilities.

The reference now being made to our members suggests that the scheme, if proceeded with, should be limited to the children of members of the three major Institutions—your own, The Institution of Civil Engineers and The Institution of Mechanical Engineers.

It may be that some children are already on the way to Australia. If this be so, and they are not already provided for, will you please communicate with this office.

Our thoughts are constantly with the people of the "Old Country"—how could it be otherwise in these terrible days!

Yours faithfully,
E. S. MACLEAN
Secretary.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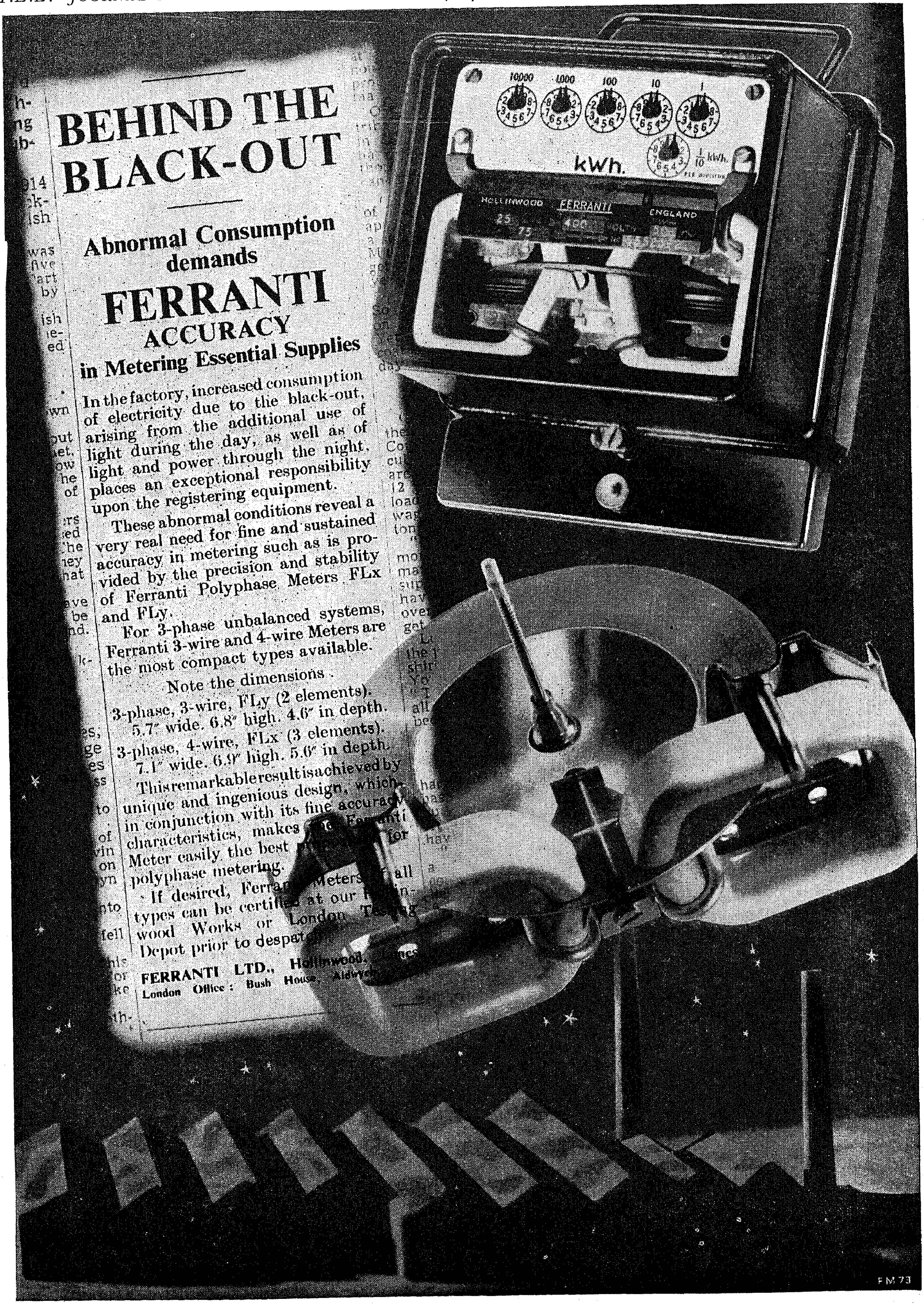
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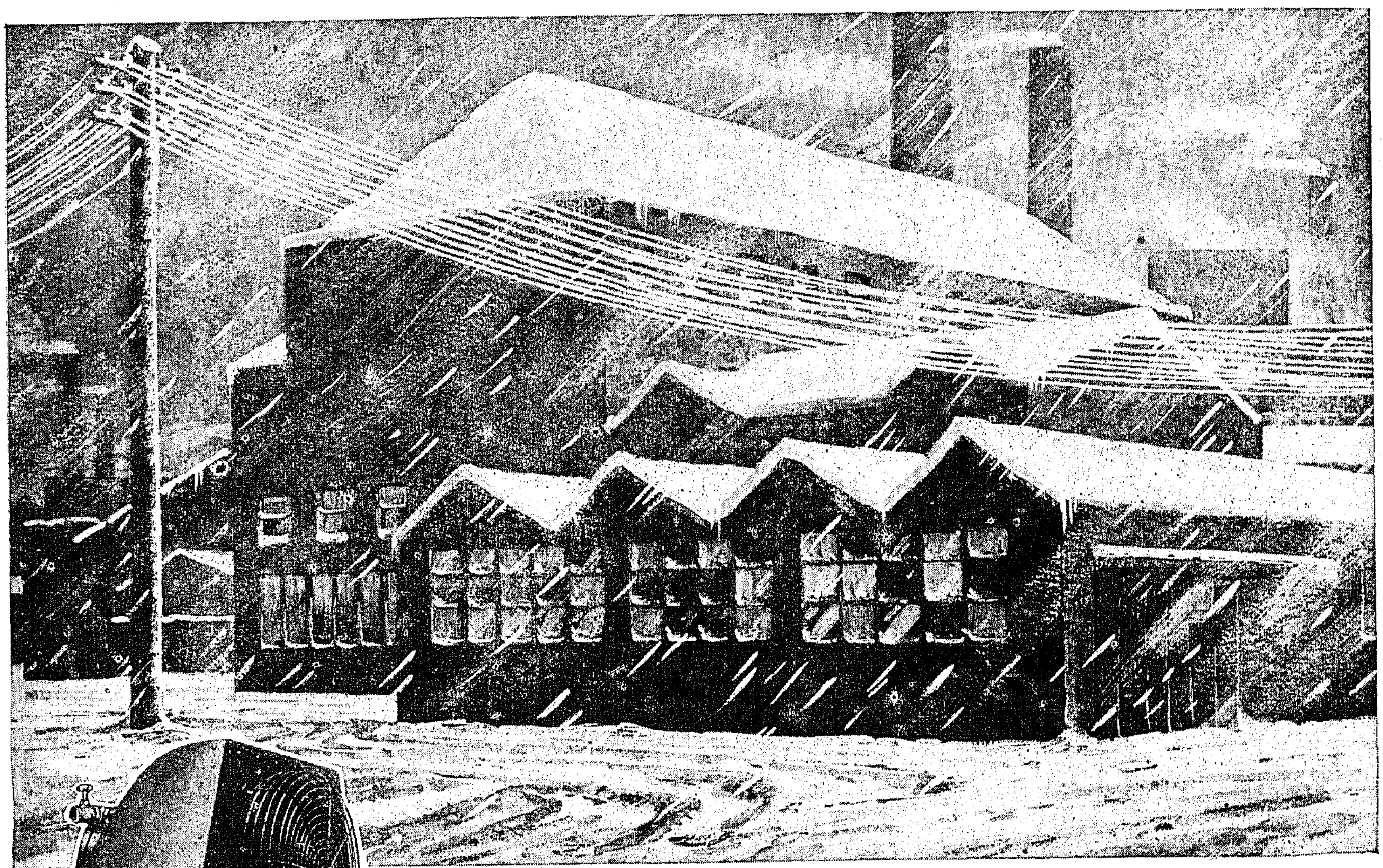

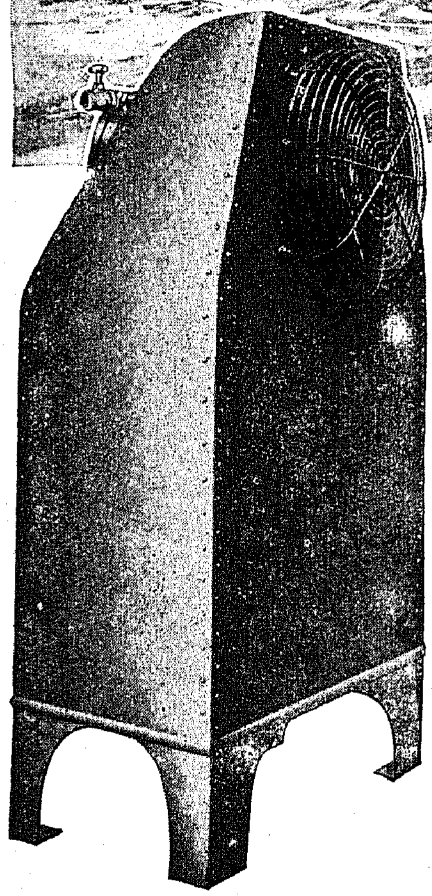

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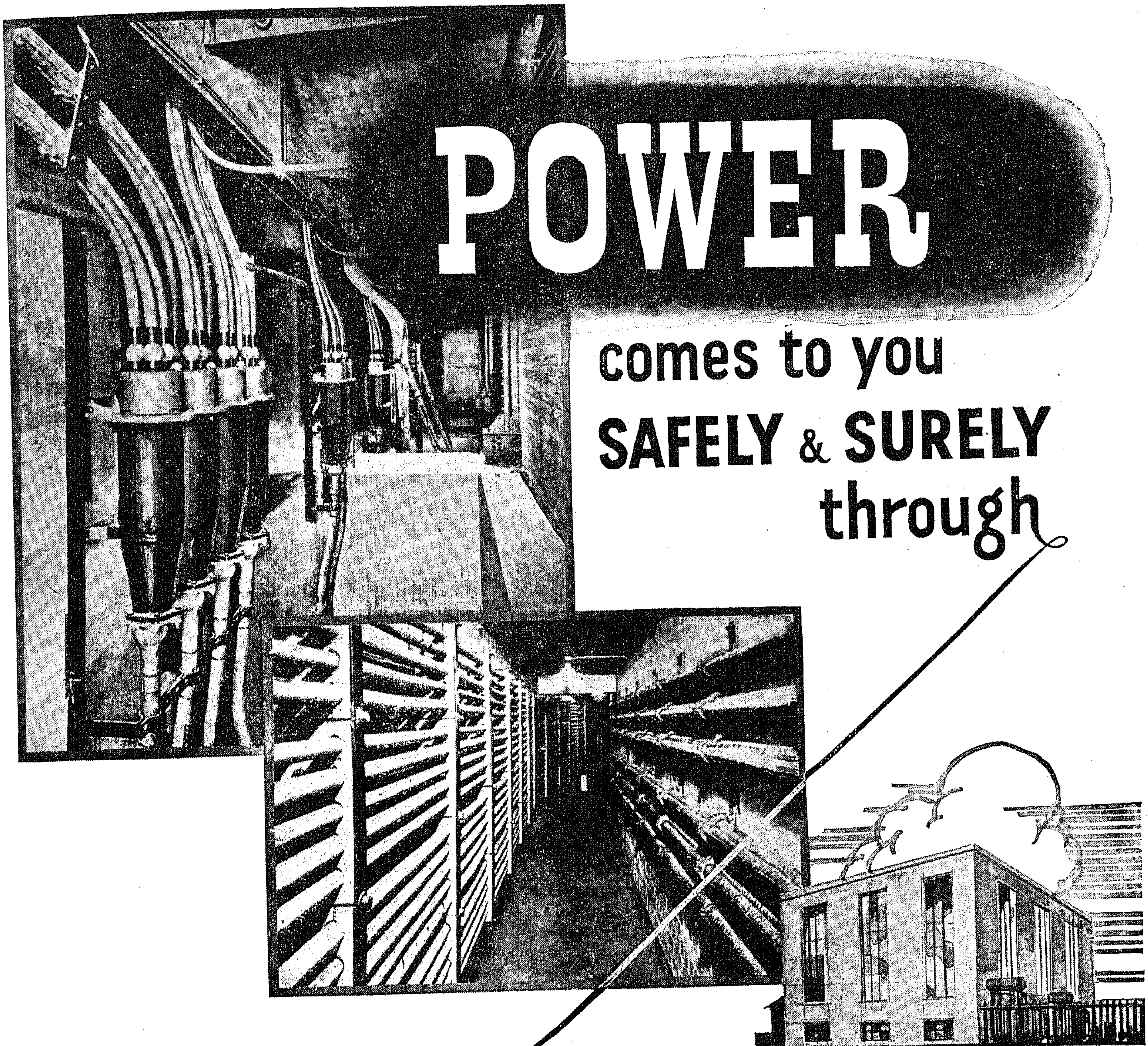

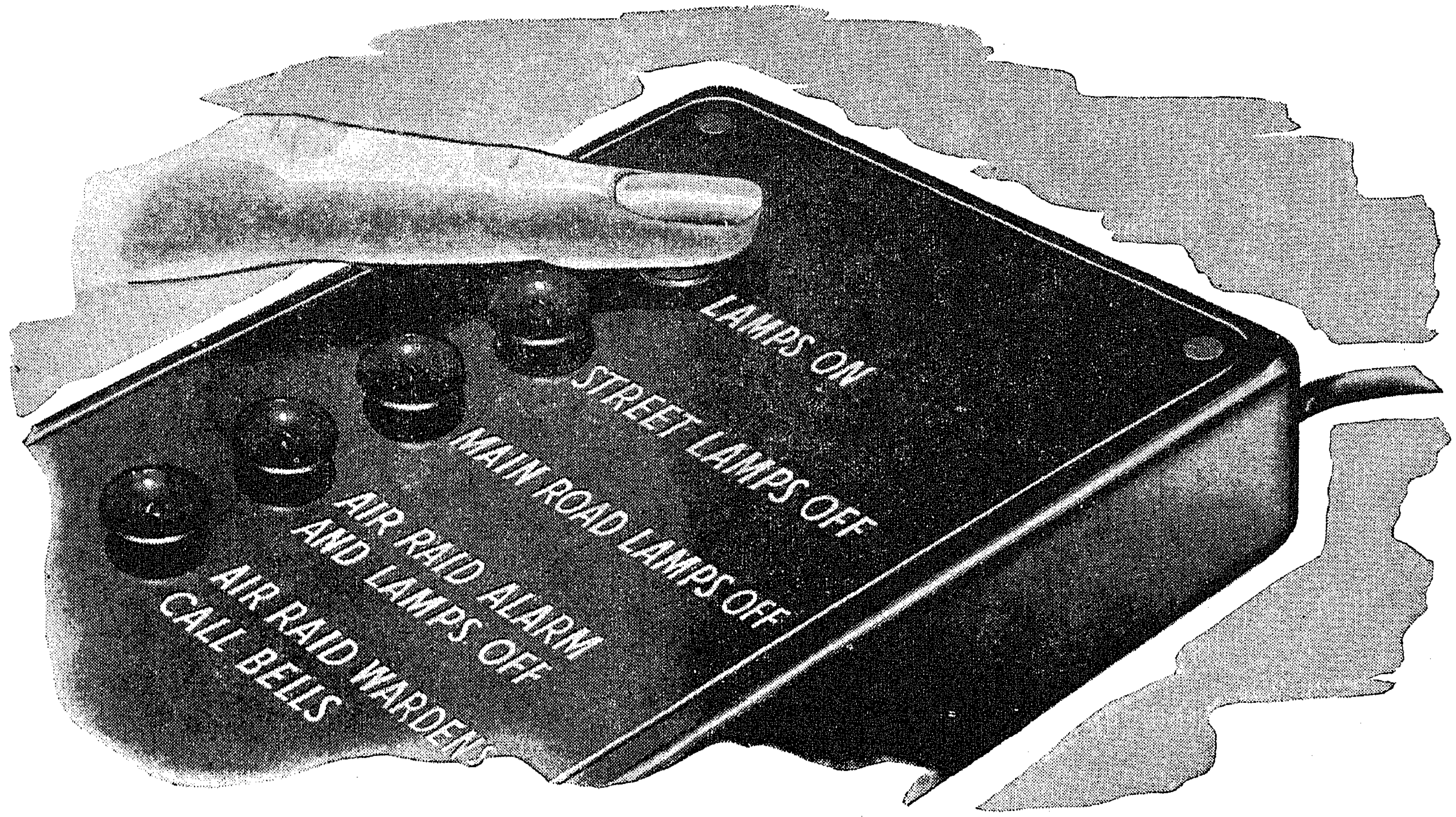

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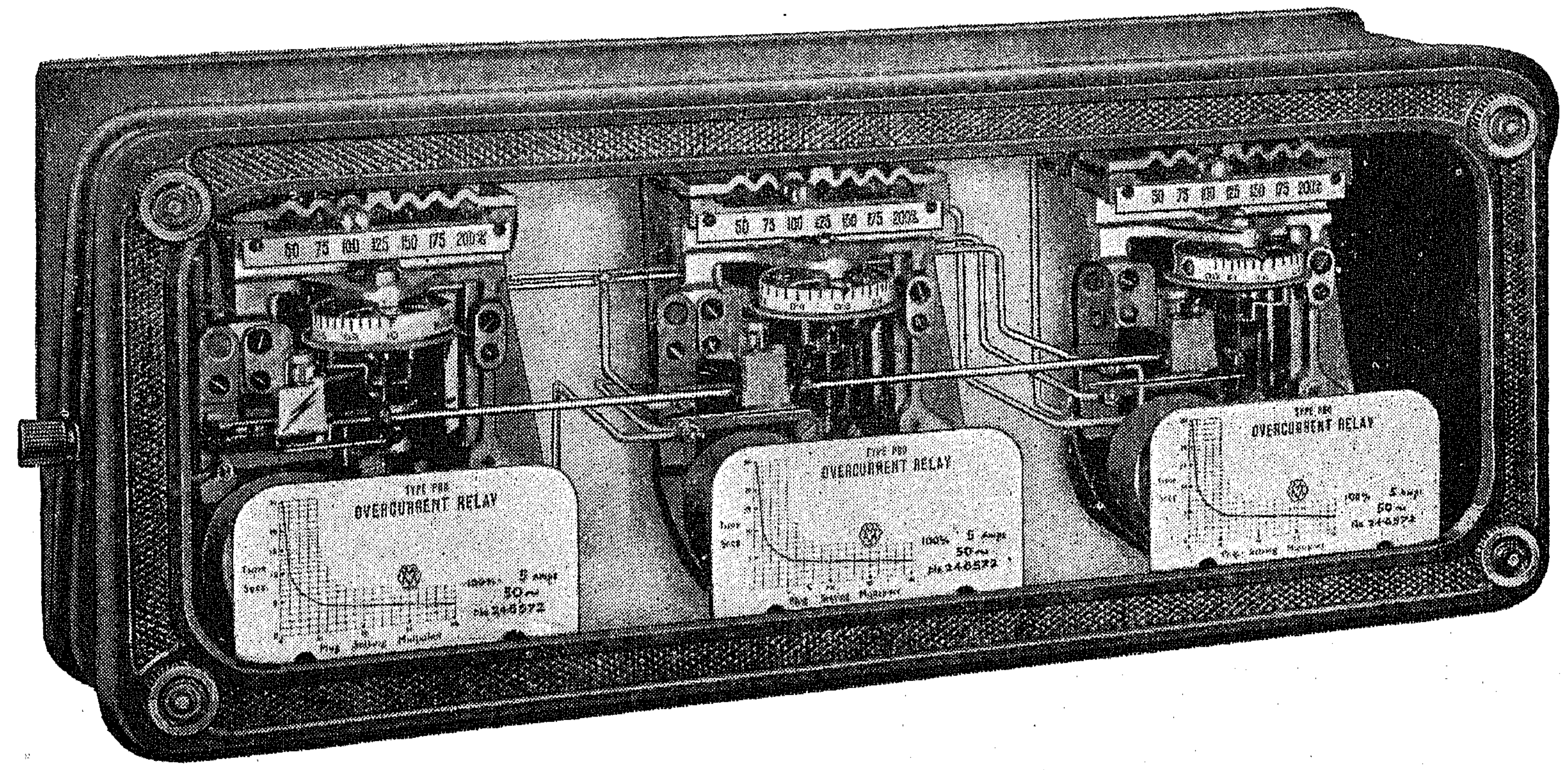

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